



Update on NO_vA Physics Potential

PAC Meeting
Aspen
20 June 2004

Gary Feldman



PAC Questions

- The main thrust of the PAC questions indicated concern over
 - what unique contribution NOvA brings to the world program,
 - how NOvA fits into a longer range Fermilab and world program,
 - and whether near and longer term optimization of NOvA are compatible.
- In this presentation, we will
 - emphasize NOvA's unique role in resolving the mass hierarchy,
 - show that there is a progression of steps that allows the resolution of the mass hierarchy for all values of the CP phase δ and an order of magnitude range of $\sin^2(2\theta_{13})$,
 - show that NOvA is optimized for all stages of this progression, even with reasonable uncertainty on the value of Δm^2 , and
 - in the process, answer all of the PAC's questions.



$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
 - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27 \Delta m_{13}^2 L/E)$
 - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27 \Delta m_{12}^2 L/E)$
 - $P_3 = \mp J \sin(\delta) \sin(1.27 \Delta m_{13}^2 L/E)$
 - $P_4 = J \cos(\delta) \cos(1.27 \Delta m_{13}^2 L/E)$
- where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times$
 $\sin(1.27 \Delta m_{13}^2 L/E) \sin(1.27 \Delta m_{12}^2 L/E)$



$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

- In matter **at oscillation maximum**, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m_{13}^2}{2\sqrt{2}G_F\rho_e} \approx 11 \text{ GeV for the earth's crust.}$$

About a $\pm 30\%$ effect for NuMI, but only a $\pm 11\%$ effect for JPARC .

However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

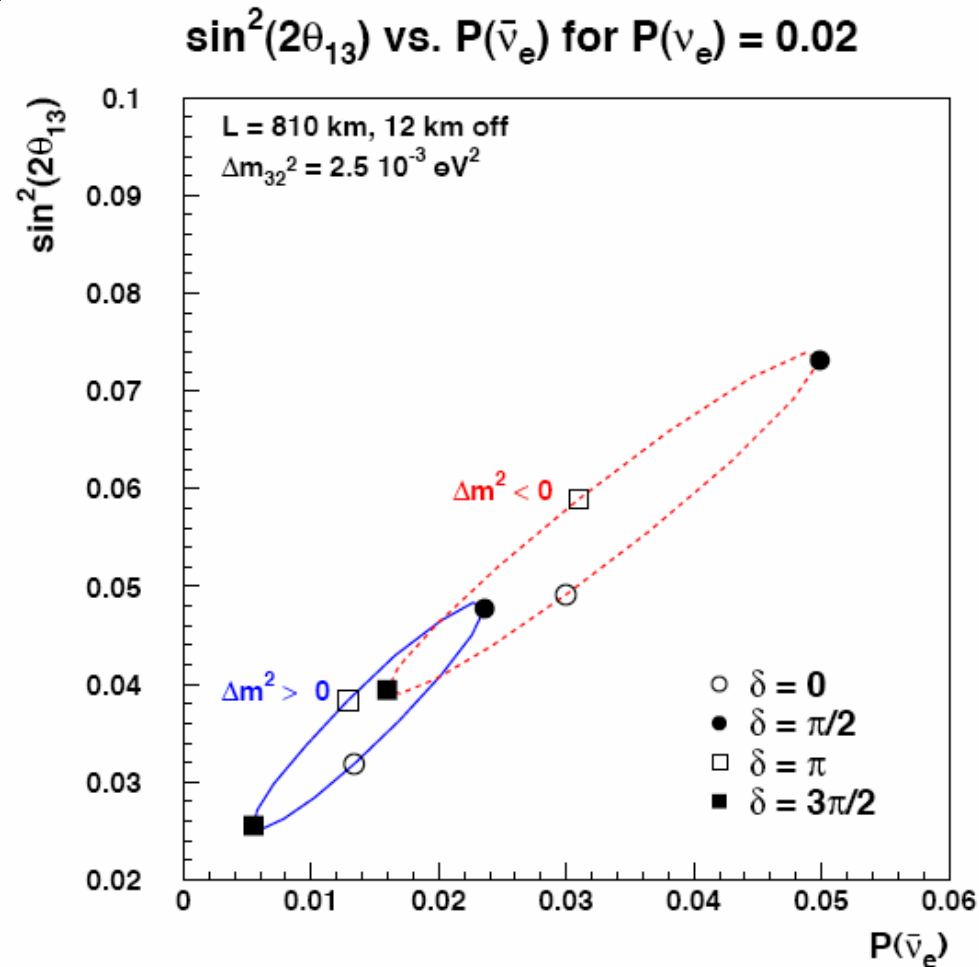


New Simulations

- **We now have revised and extended simulations**
 - **Correct an error in the fiducial containment**
 - **Correct a miscommunication on the assumed flux**
 - **Optimized for neutrinos and antineutrinos at**
 - **6, 8, 10, 12, 14, and 16 km off-axis for $\Delta m^2 = 0.0025 \text{ eV}^2$**
 - **8, 10, 12, and 14 km off-axis for $\Delta m^2 = 0.0020 \text{ eV}^2$**

Reminder of the Problem

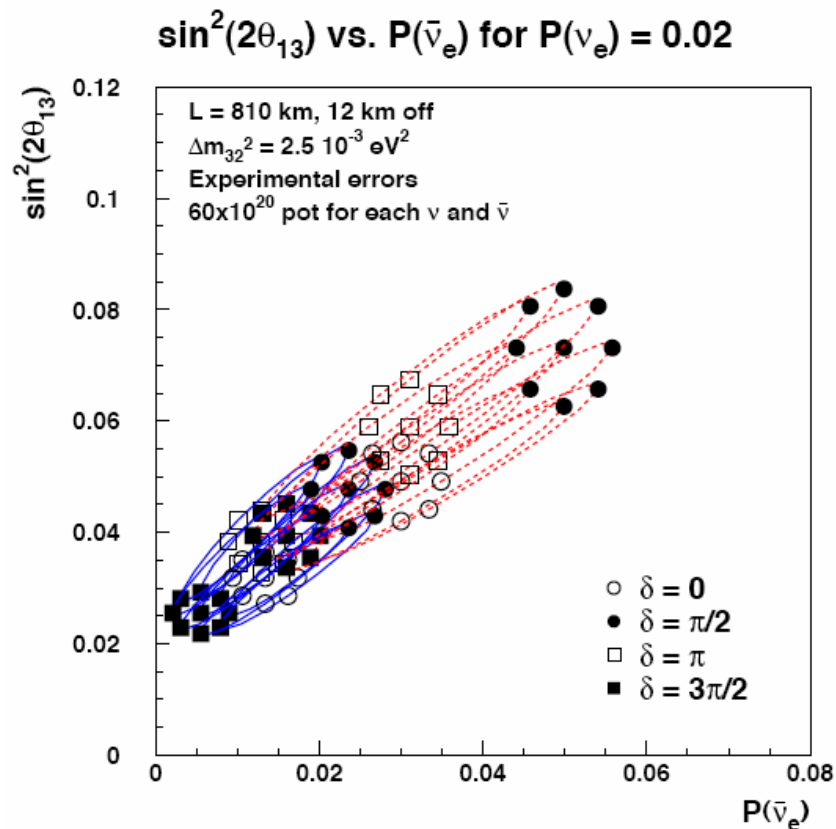
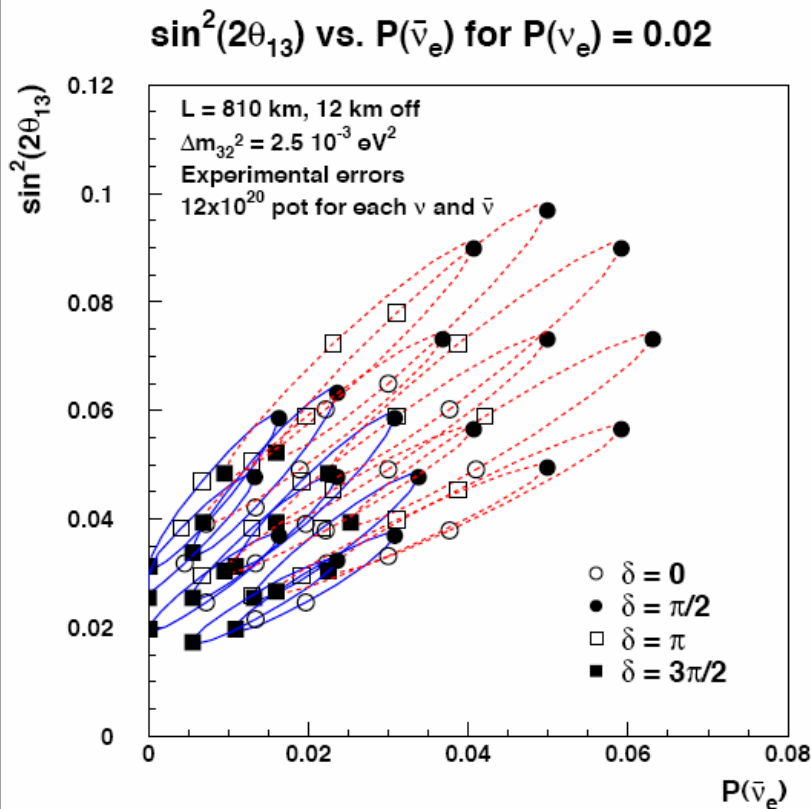
Part 1





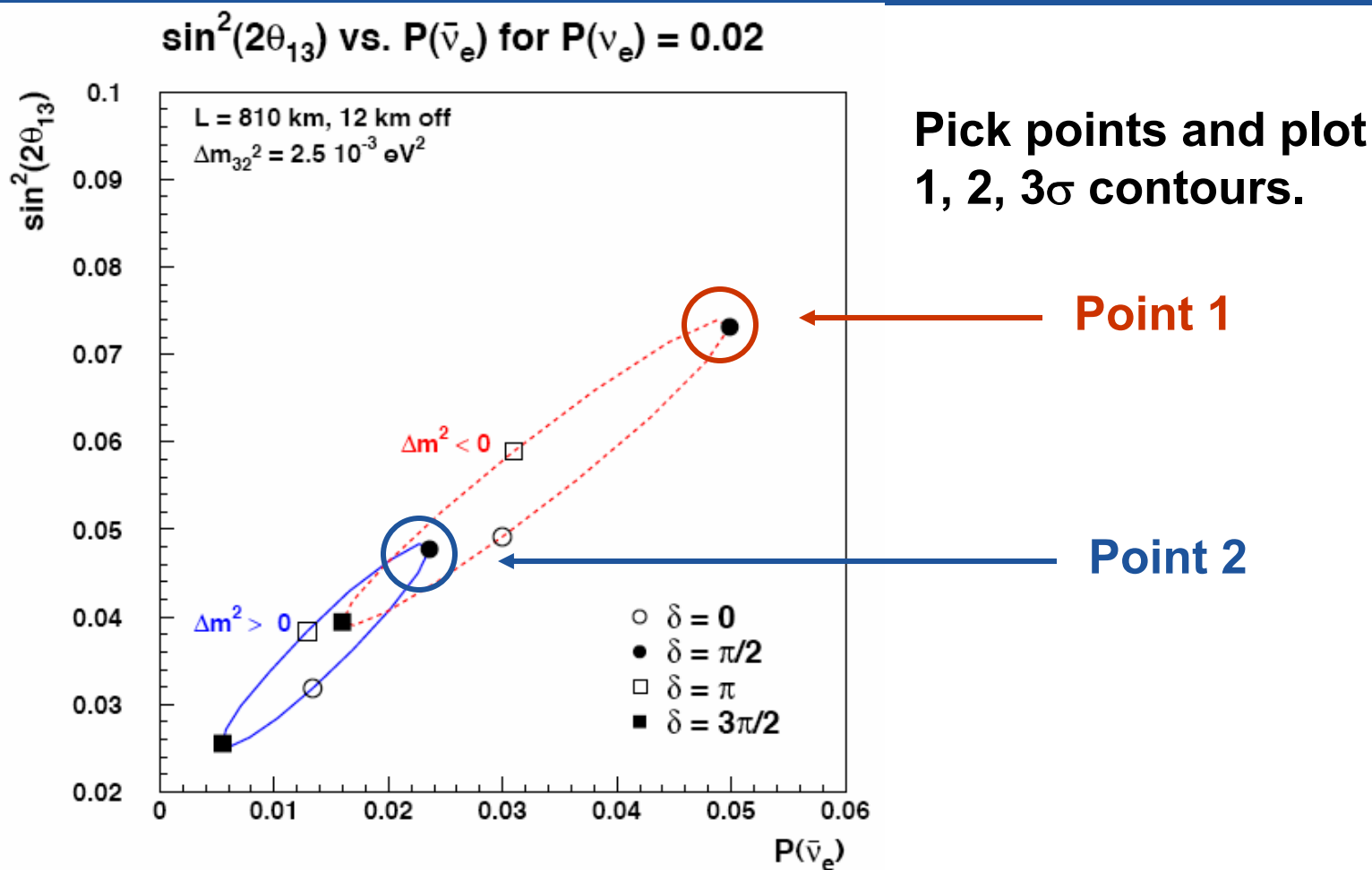
NOVA

Smearing of the Ellipses due to Experimental Errors



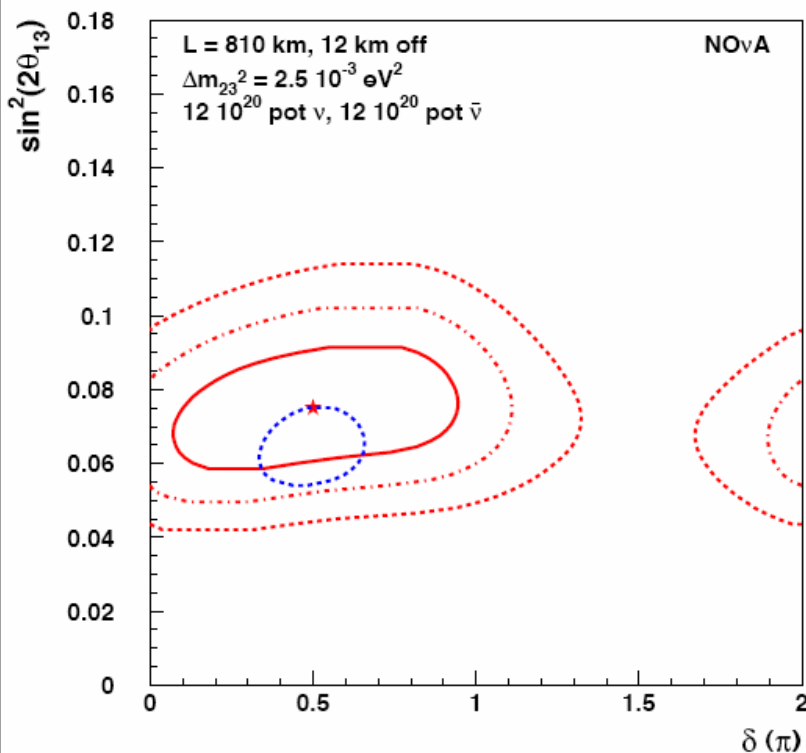
Proton Driver

More Conventional Approach to Smearing

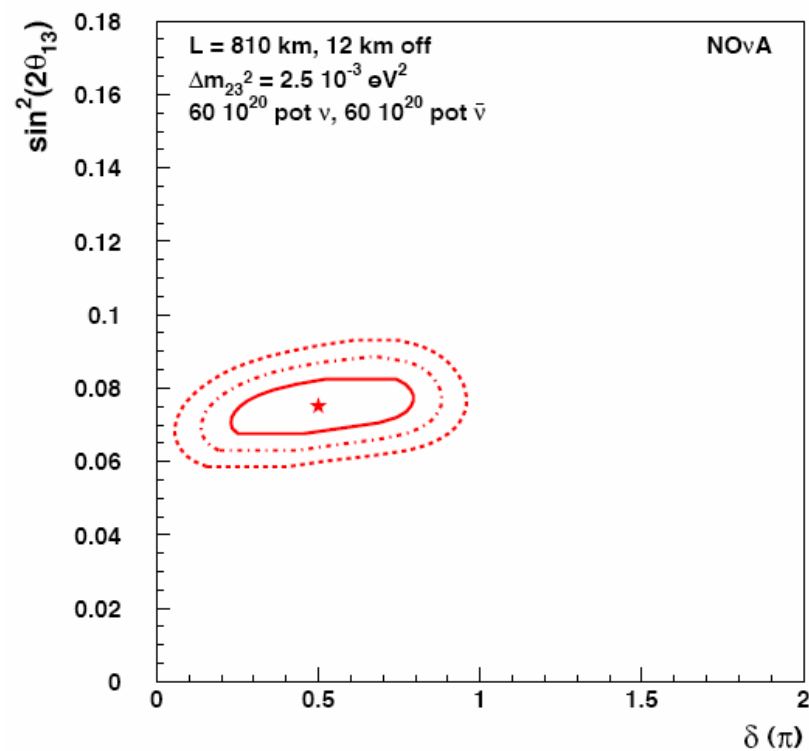


Point 1

1, 2, 3 σ Contours for Starred Point, Neg Δm^2



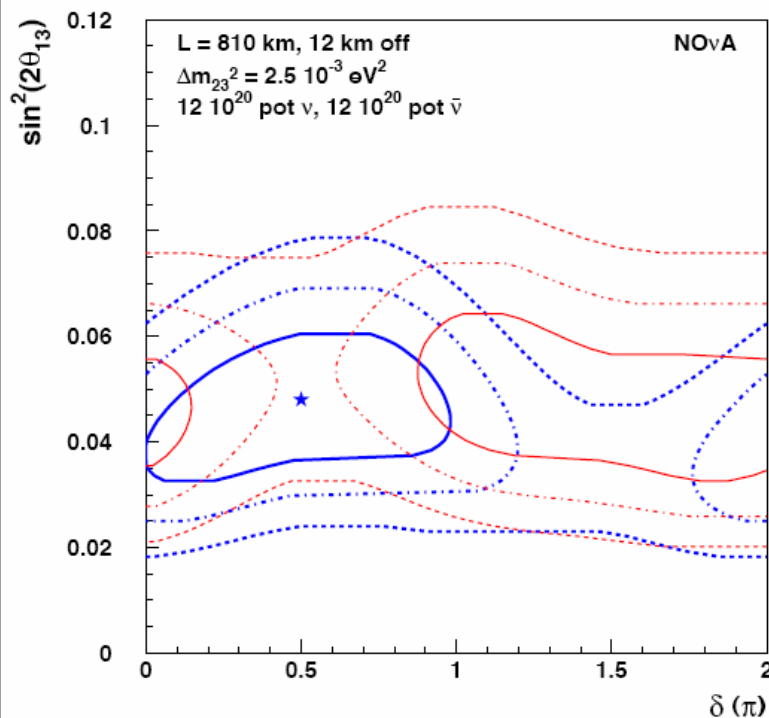
1, 2, 3 σ Contours for Starred Point, Neg Δm^2



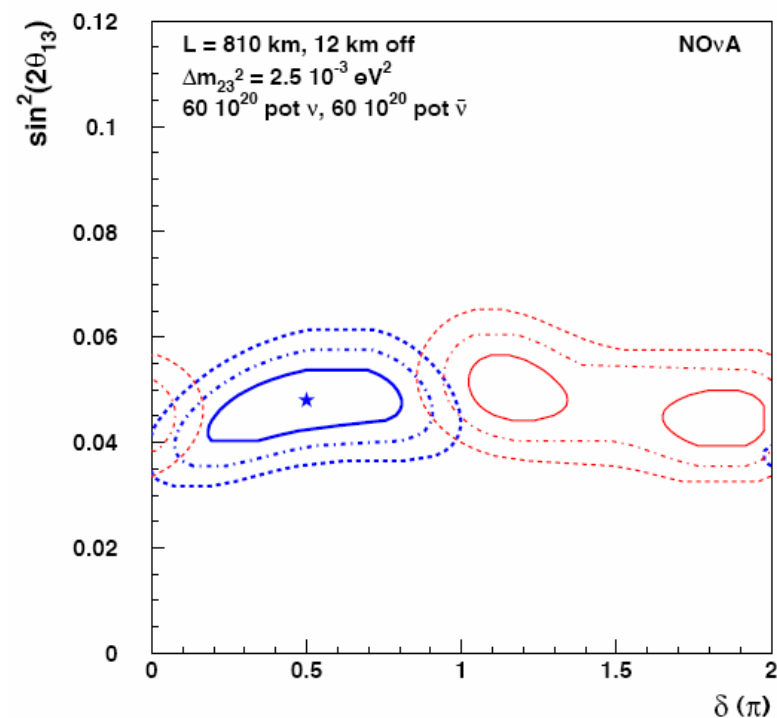
Proton Driver

Point 2

1, 2, 3 σ Contours for Starred Point, Pos Δm^2



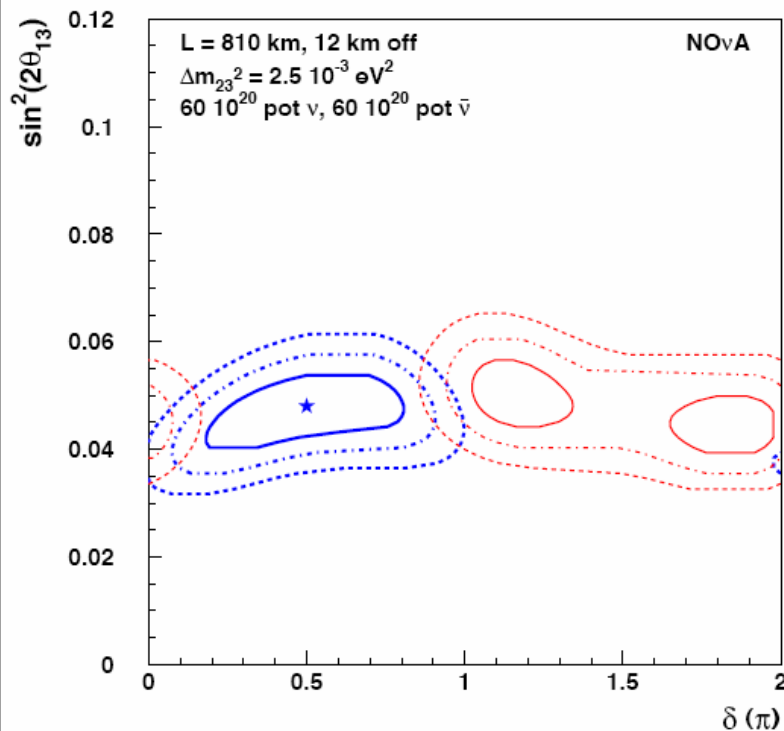
1, 2, 3 σ Contours for Starred Point, Pos Δm^2



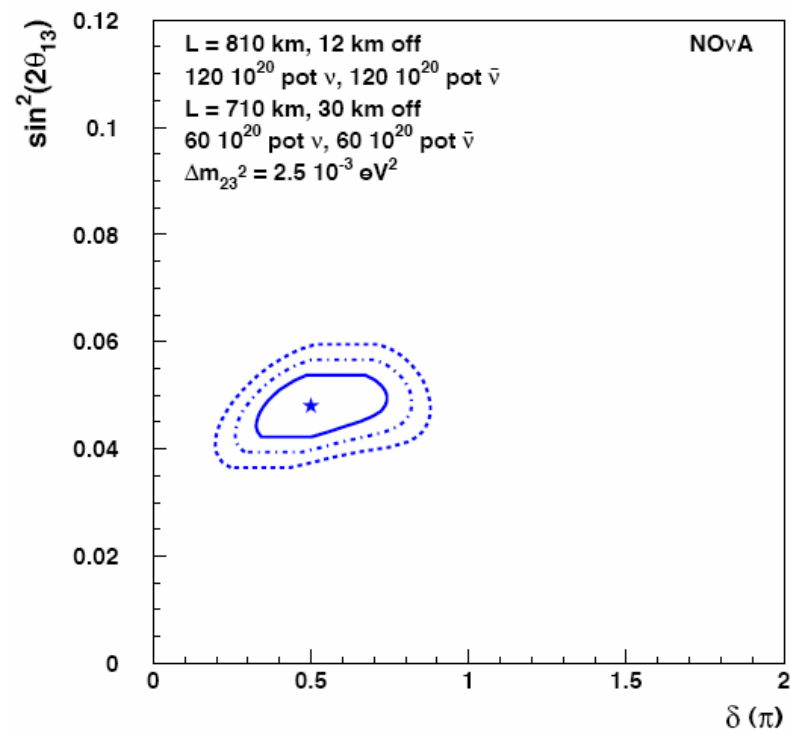
Proton Driver

Point 2

1, 2, 3 σ Contours for Starred Point, Pos Δm^2



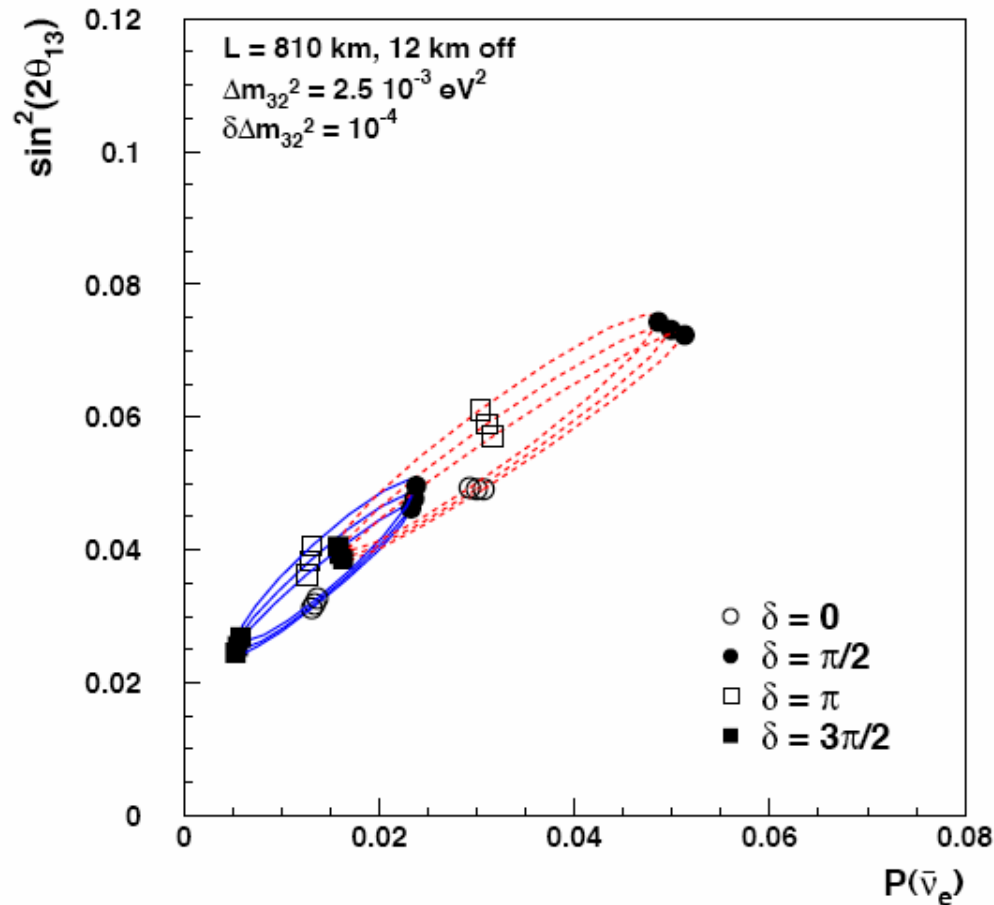
1, 2, 3 σ Contours for Starred Point, Pos Δm^2



**2nd Off-Axis
Detector**

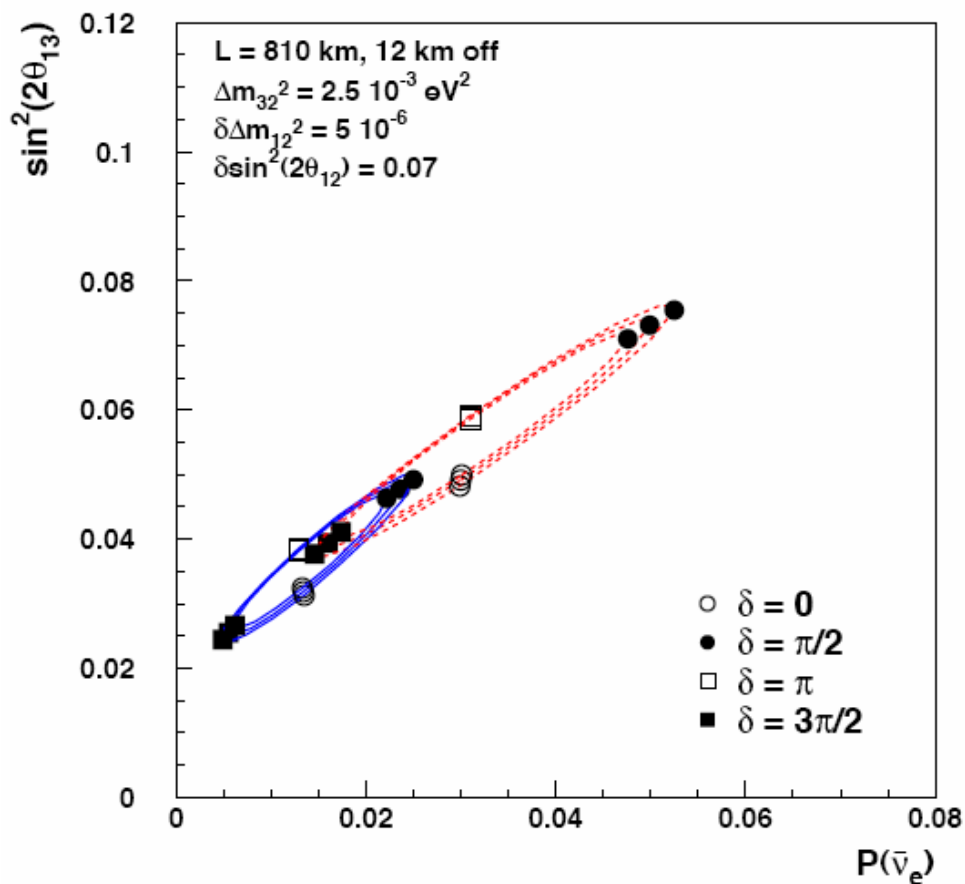
Smearing of the Ellipses due to $\delta\Delta m_{32}^2$

$\sin^2(2\theta_{13})$ vs. $P(\bar{\nu}_e)$ for $P(\nu_e) = 0.02$



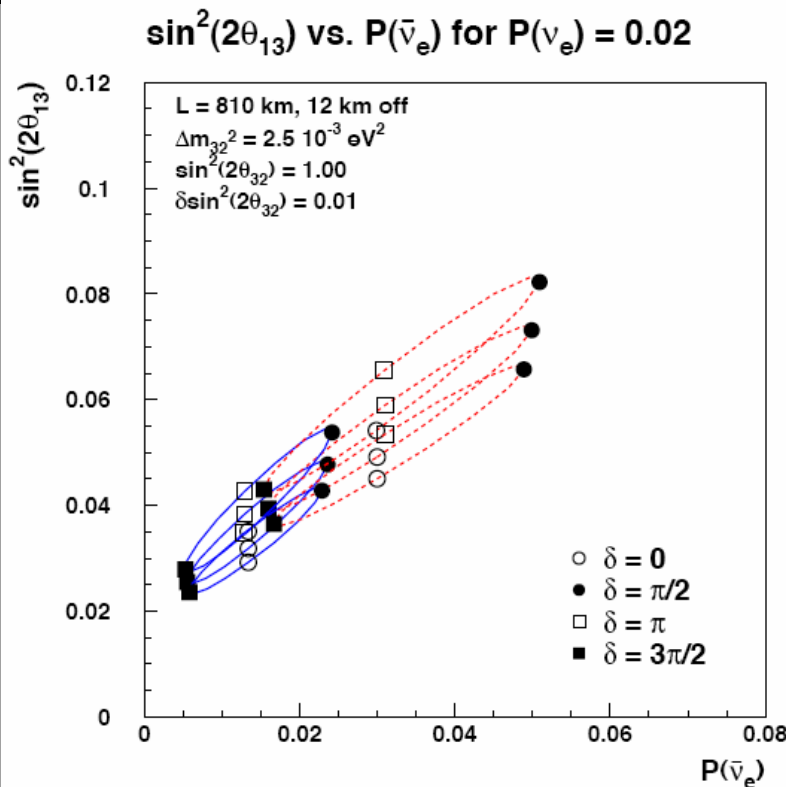
Smearing of the Ellipses due to $\delta\Delta m_{12}^2$ and $\sin^2(2\theta_{12})$

$\sin^2(2\theta_{13})$ vs. $P(\bar{\nu}_e)$ for $P(\nu_e) = 0.02$

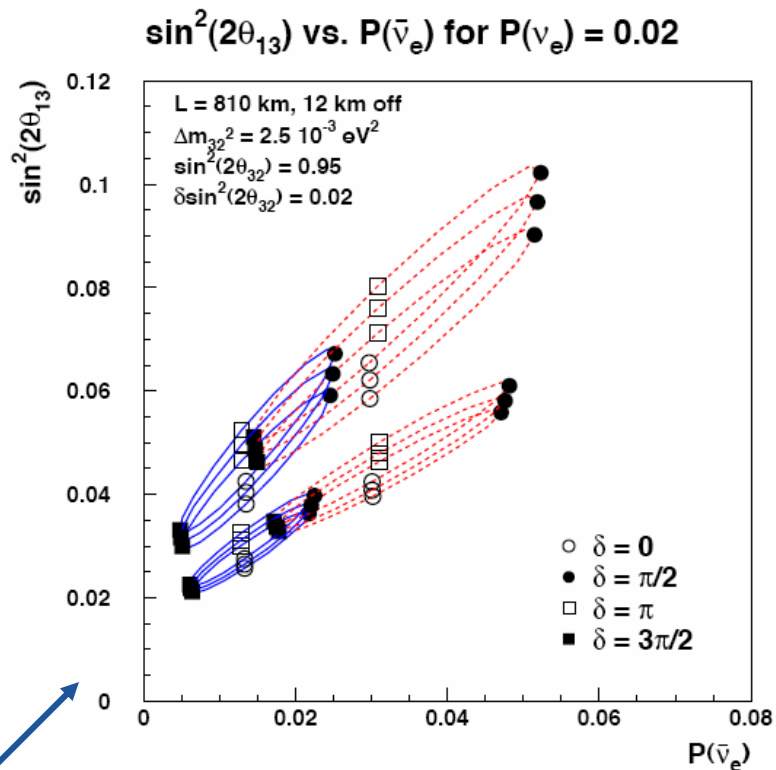




Smearing of the Ellipses due to $\sin^2(2\theta_{32})$



$$\sin^2(2\theta_{23}) = 1.0$$

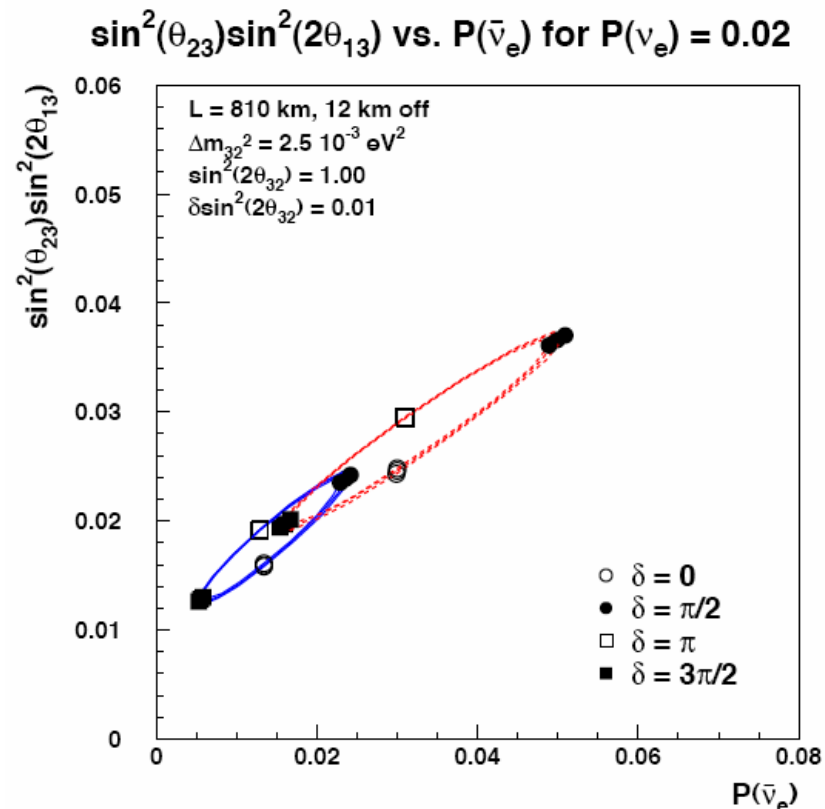
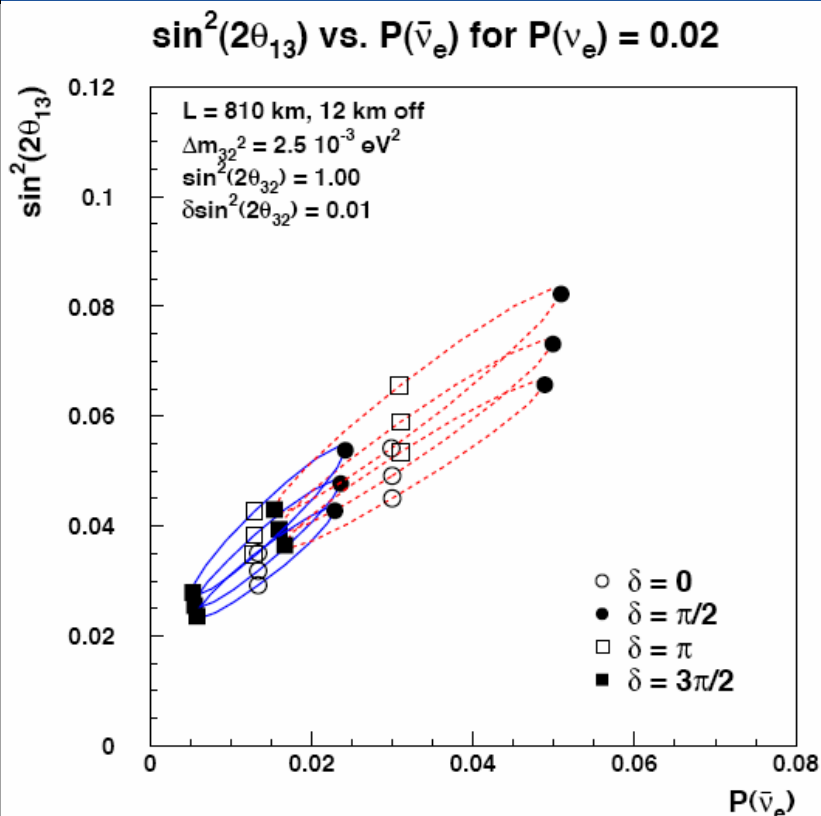


$$\sin^2(2\theta_{23}) = 0.95$$

An ambiguity this large could be resolved by the comparison of accelerator and reactor experiments.

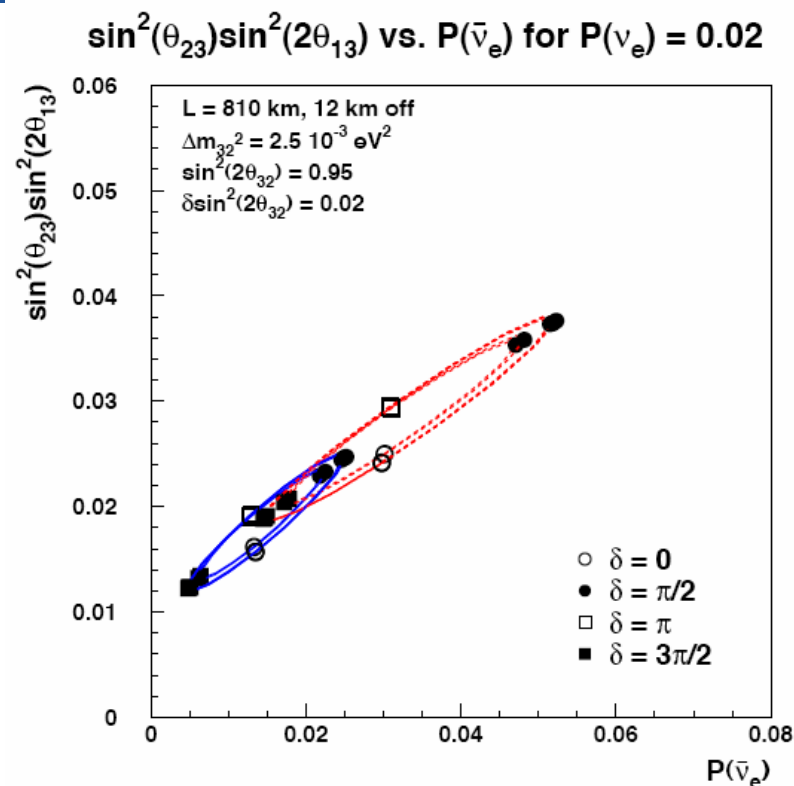
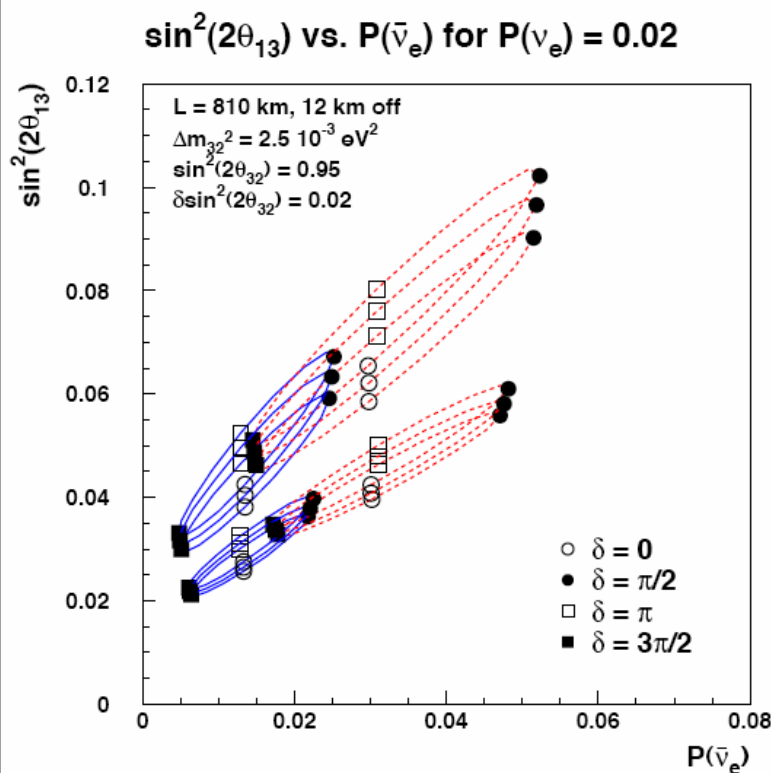


Smearing of the Ellipses due to $\sin^2(2\theta_{32})$



This ambiguity is benign with respect to measuring the mass hierarchy and CP with accelerator experiments, as seen by a change of variable.

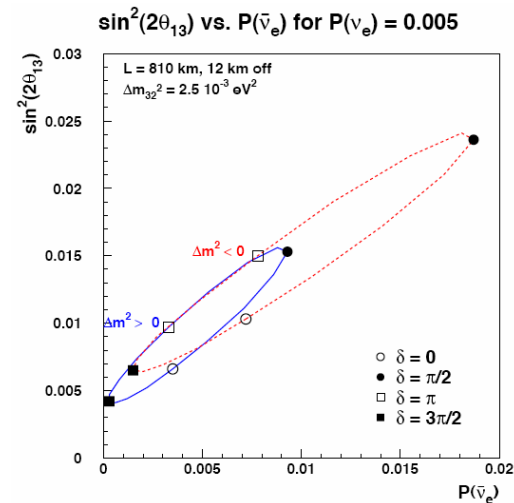
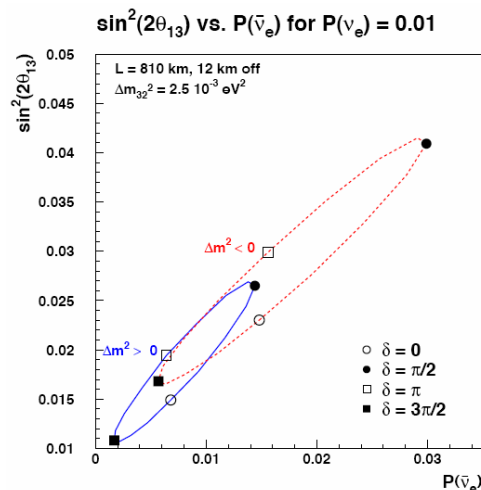
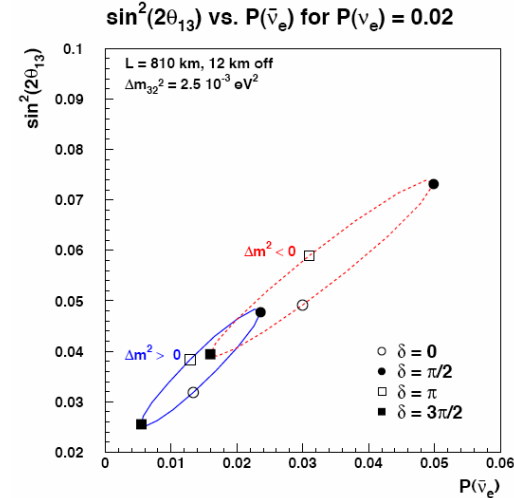
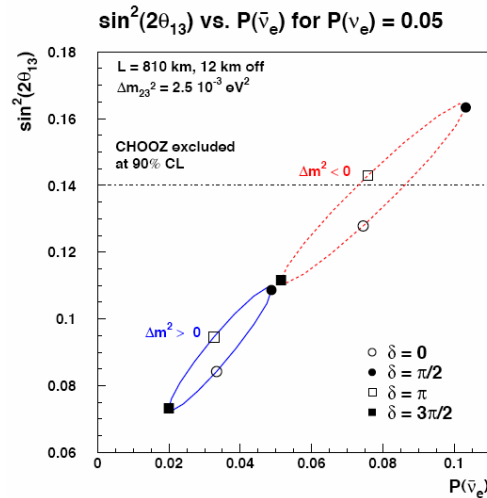
Smearing of the Ellipses due to $\sin^2(2\theta_{32})$



Change of variable

Reminder of the Problem

Part 1

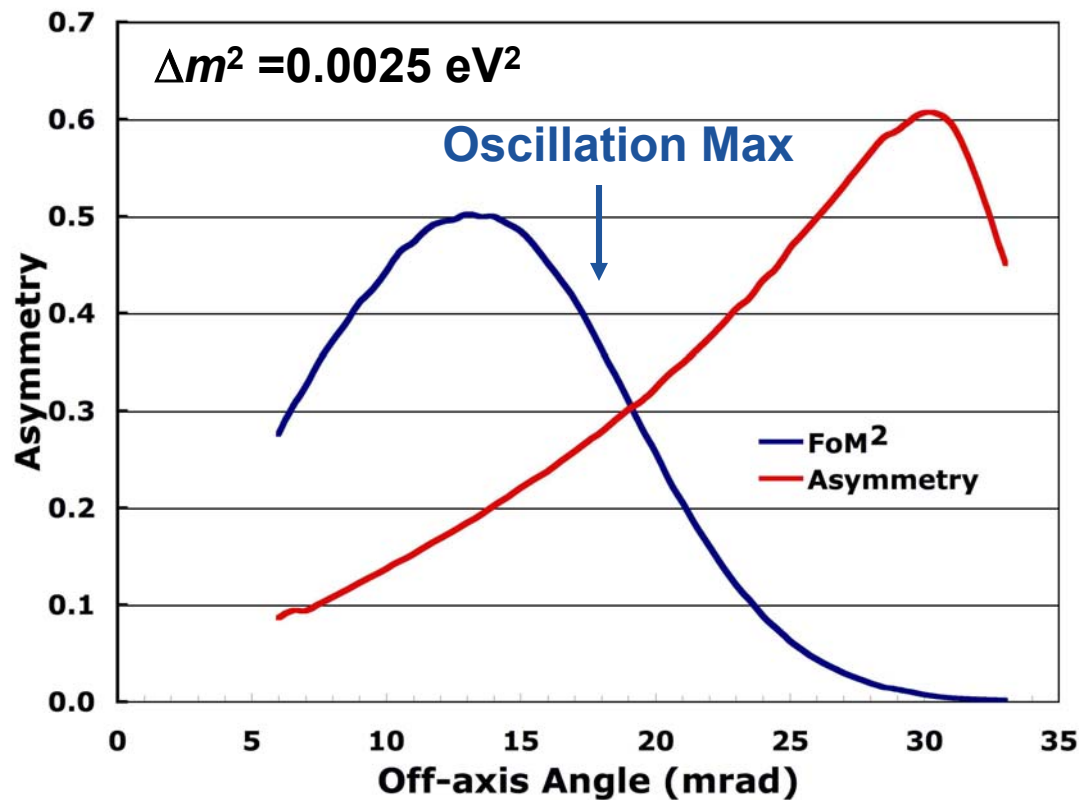




Reminder of the Problem

Part 2

FoM² and Asymmetry vs. Angle

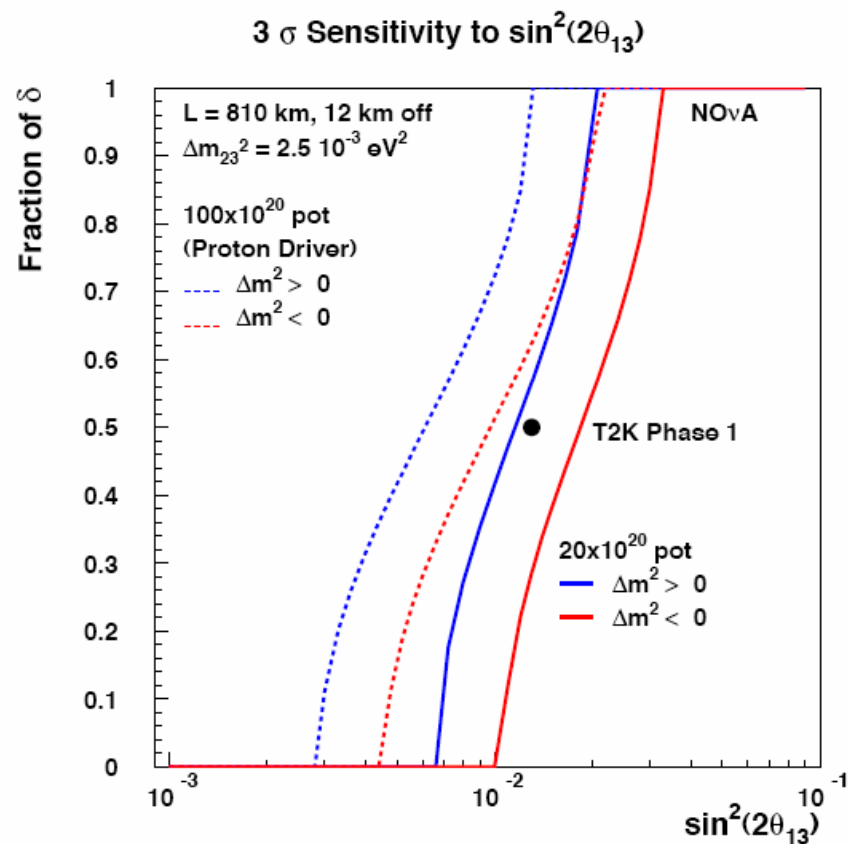
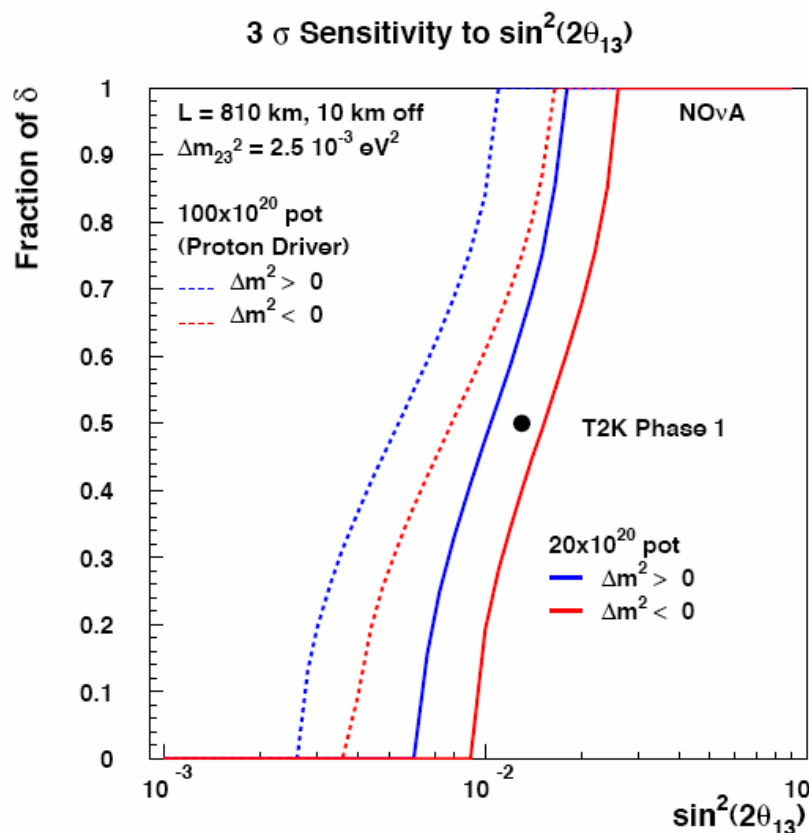


$$\text{FoM} = \frac{\text{signal}}{\sqrt{\text{background}}}$$

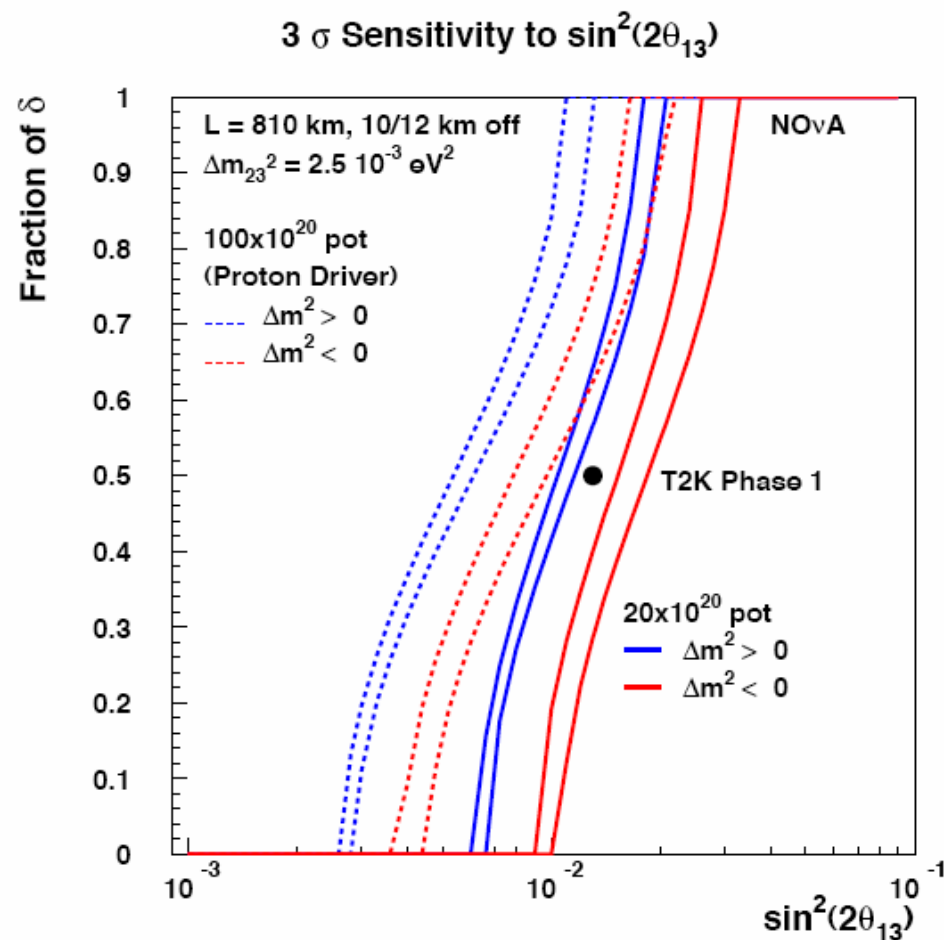
Asymmetry =

$$\left(\frac{\sigma_{\nu} - \sigma_{\bar{\nu}}}{\sigma_{\nu} + \sigma_{\bar{\nu}}} \right)$$

3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$

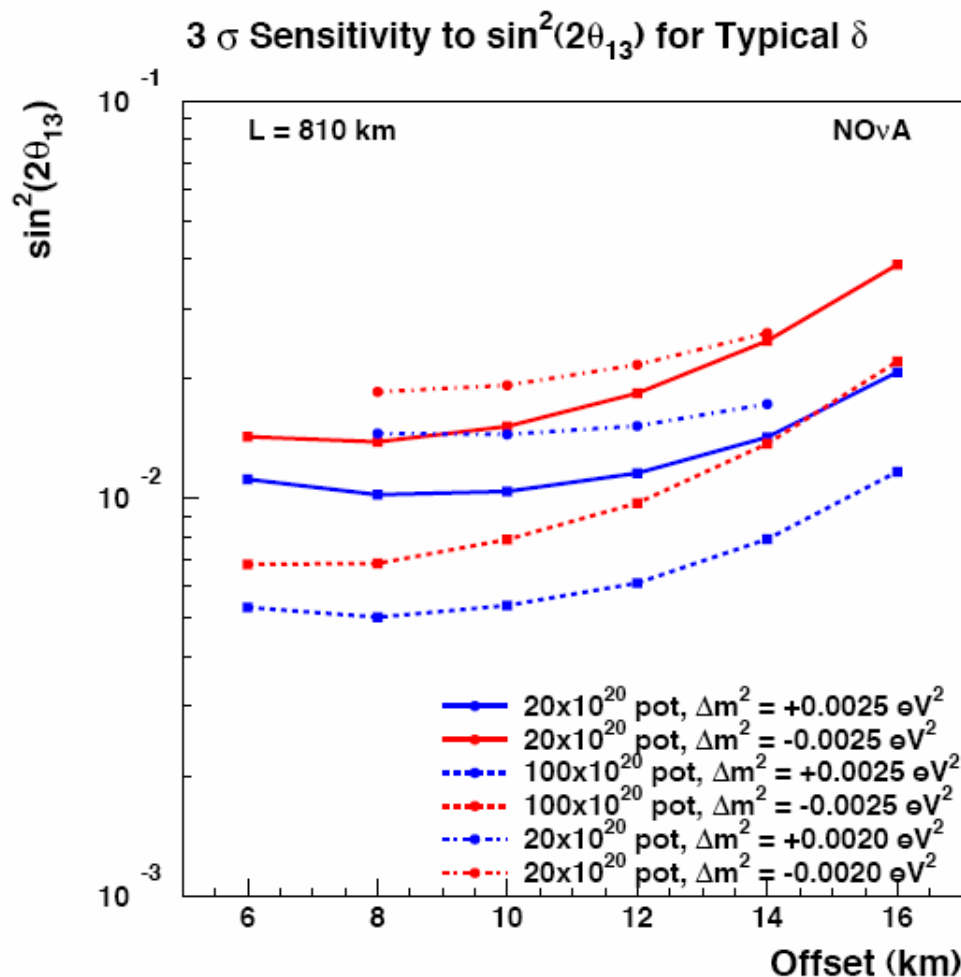


Comparison of 10 and 12 km



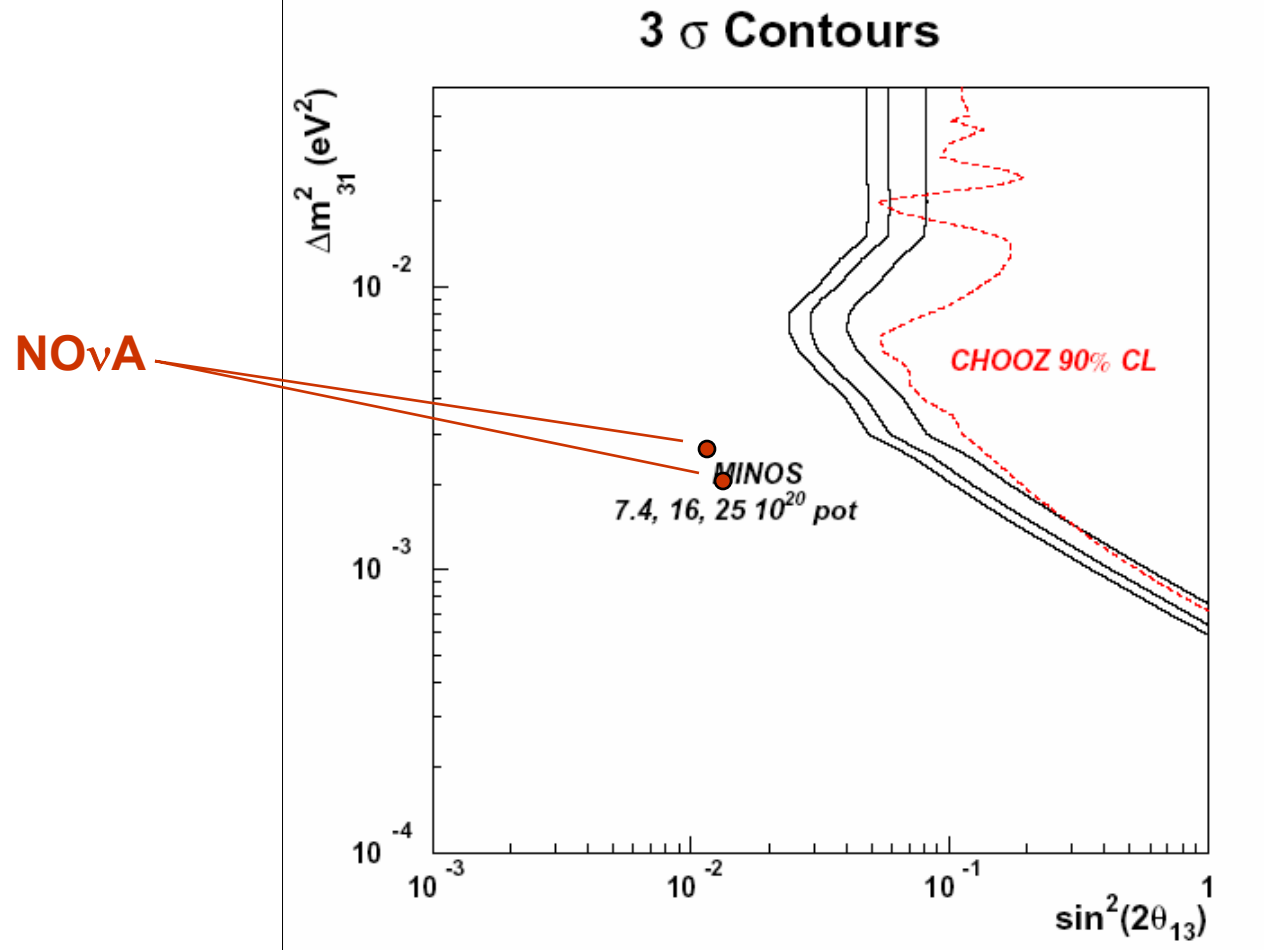


3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$ vs. Off-Axis Distance



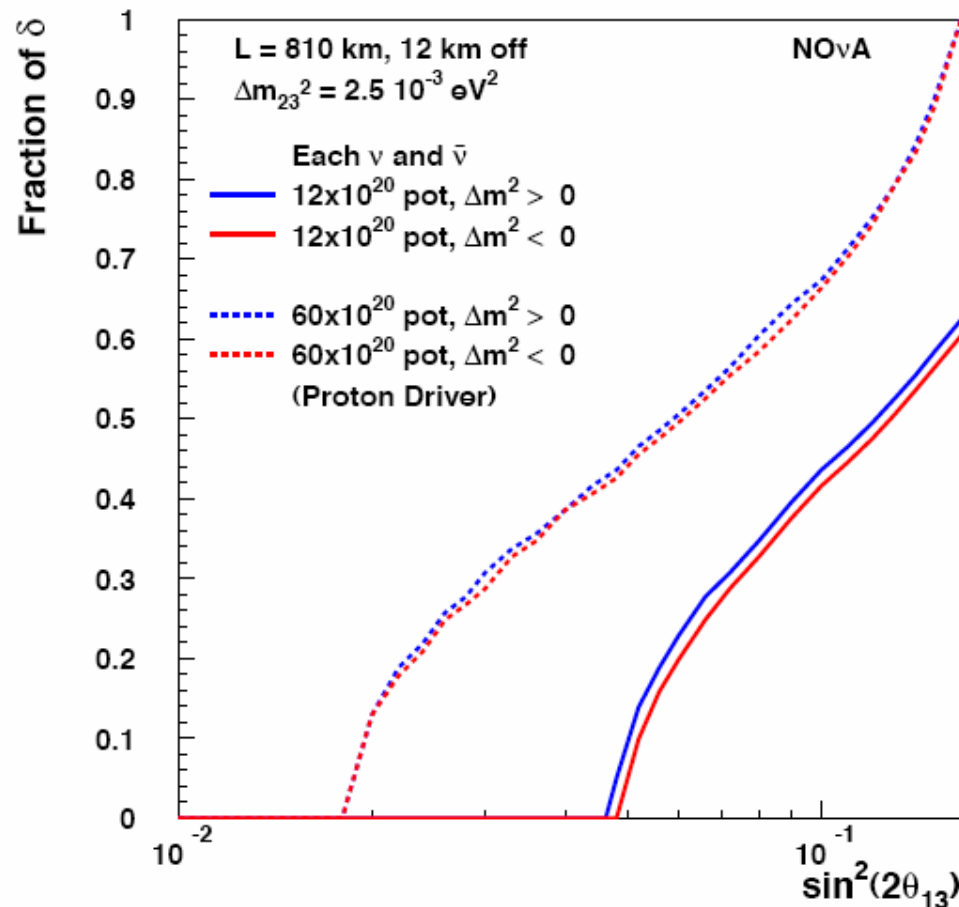
Note: There is a loss of sensitivity for $\Delta m^2 = 0.002$ eV², but not a loss of range, since the CHOOZ limit is correspondingly weaker there.

Comparison to MINOS

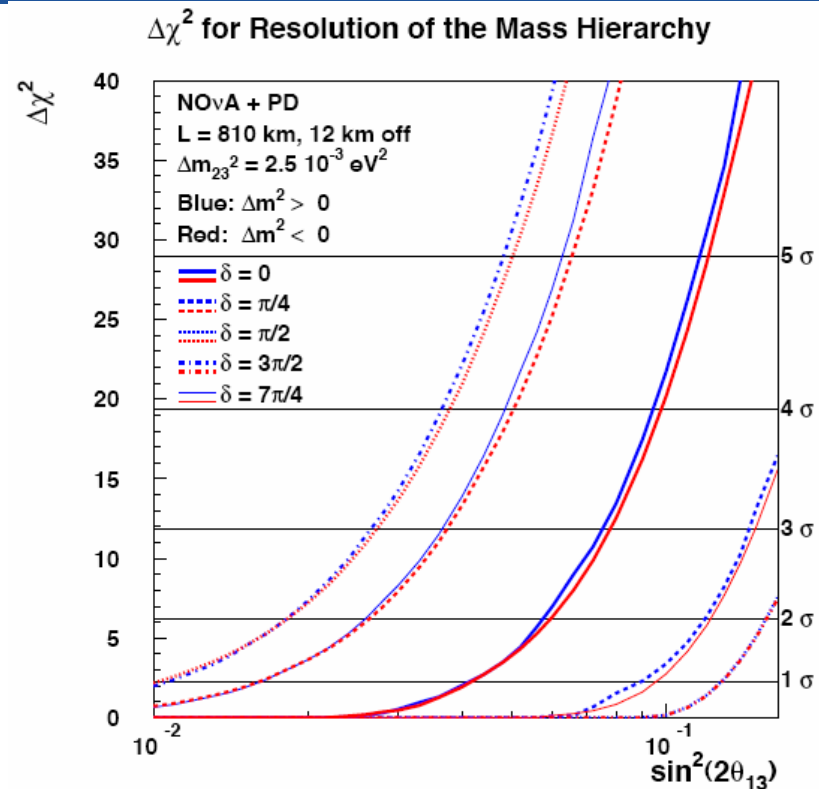
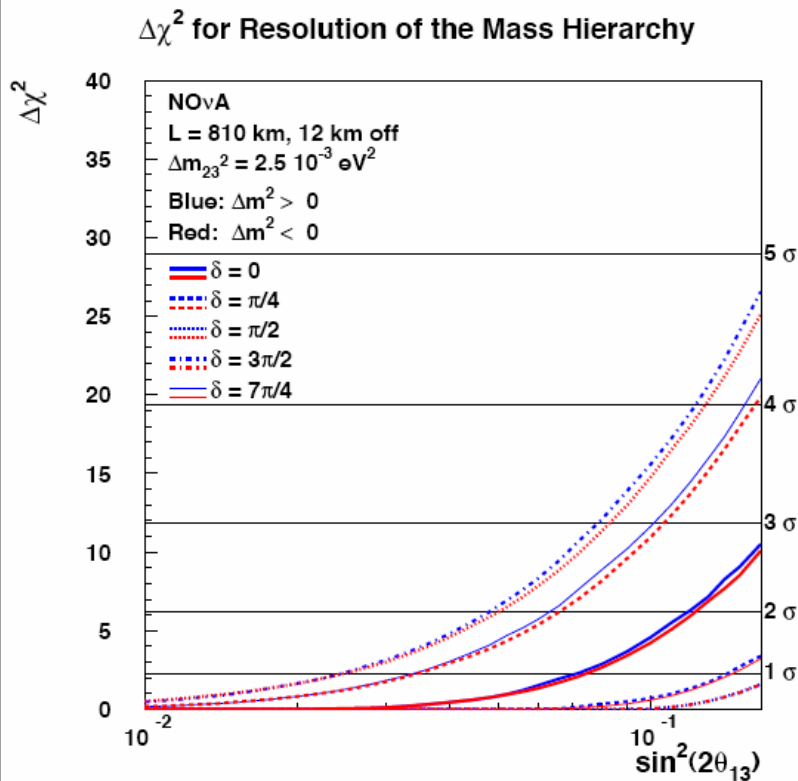


95% CL Resolution of the Mass Hierarchy

2 σ Resolution of the Mass Hierarchy



Resolution of the Mass Hierarchy



Proton Driver

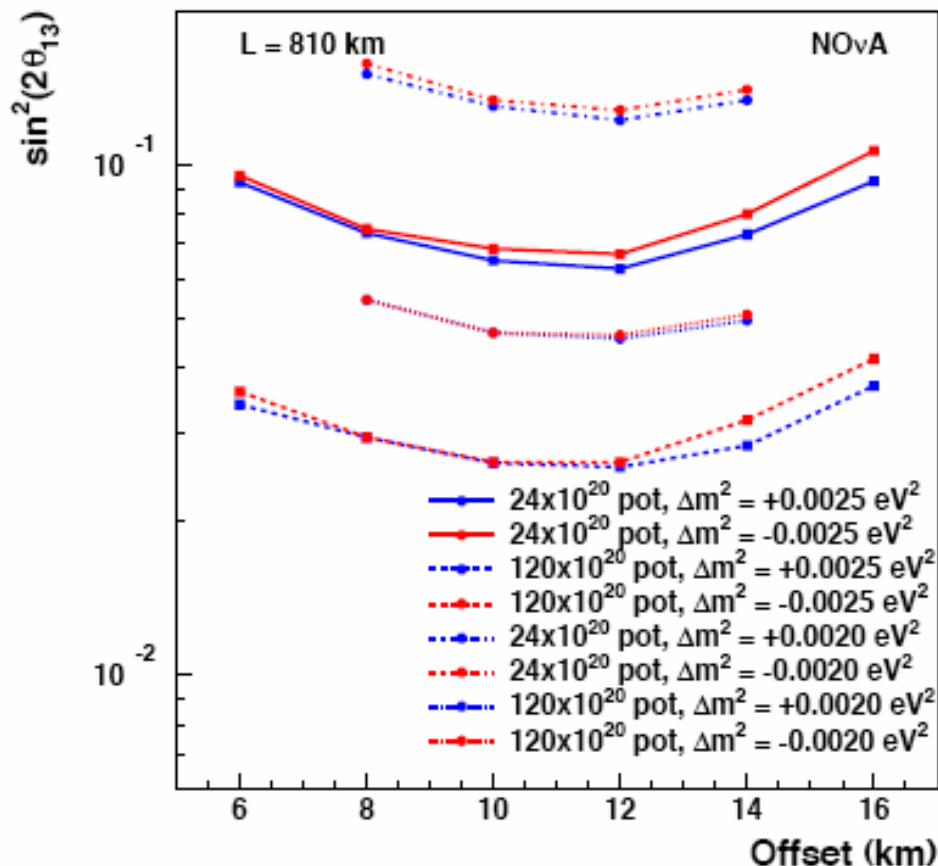
Note that a Proton Driver changes a 1σ effect into a 3σ effect.



NOvA

Mass Hierarchy Resolution vs. Off-Axis Distance

2 σ Mass Hierarchy Resolution for 1st Quartile δ

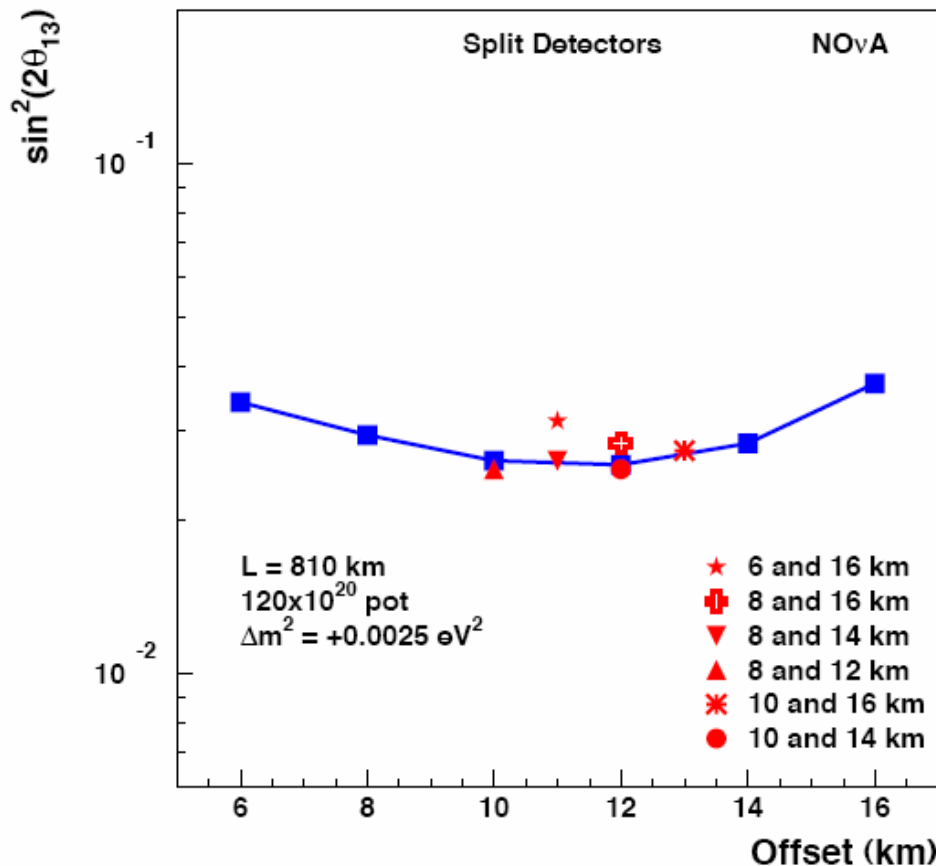


12 km off-axis
is best for both
 $\Delta m^2 = 0.0025$ and
 $\Delta m^2 = 0.0020$ eV 2

Note that best SK
analysis ("L/E")
has best value at
0.0025 eV 2 and
90% C.L. lower limit
at 0.0019 eV 2 .

PAC Question: Are two (1/2) Detectors Better than One?

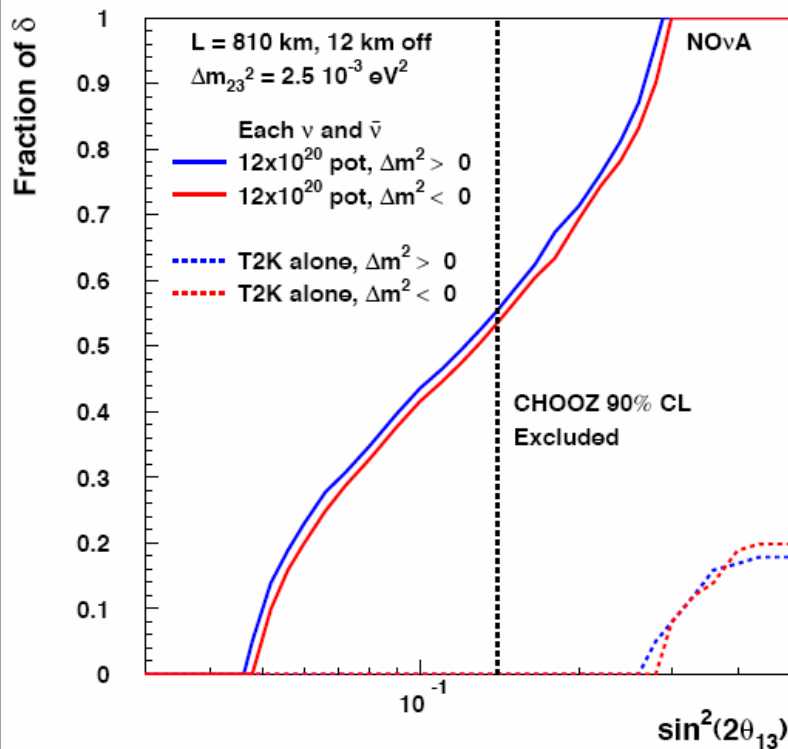
2 σ Mass Hierarchy Resolution for 1st Quartile δ



Answer: Yes, but not by enough to overcome the fiducial and infrastructure costs.

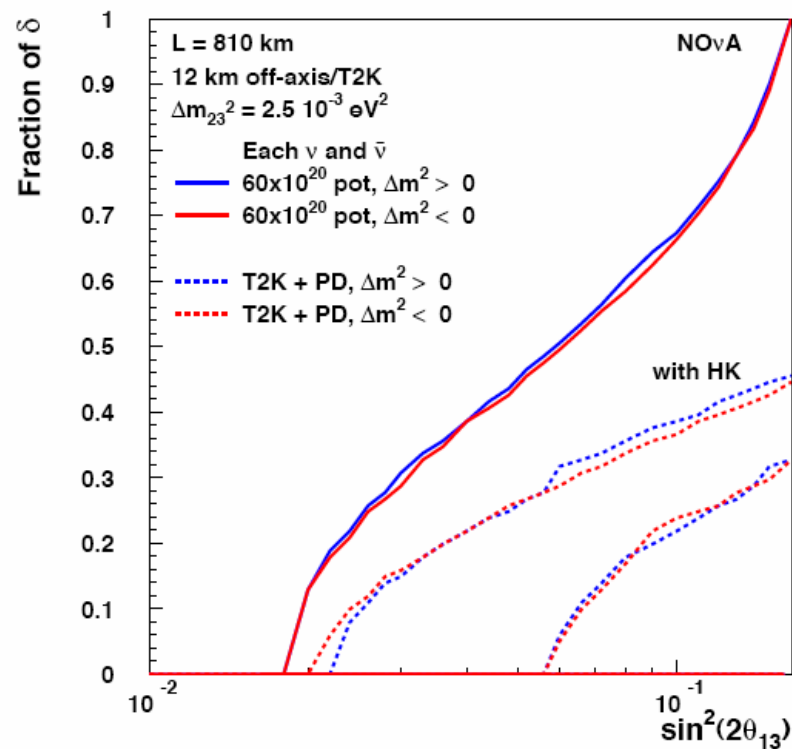
NOvA Alone vs. T2K Alone

2 σ Resolution of the Mass Hierarchy



Note change of horizontal scale

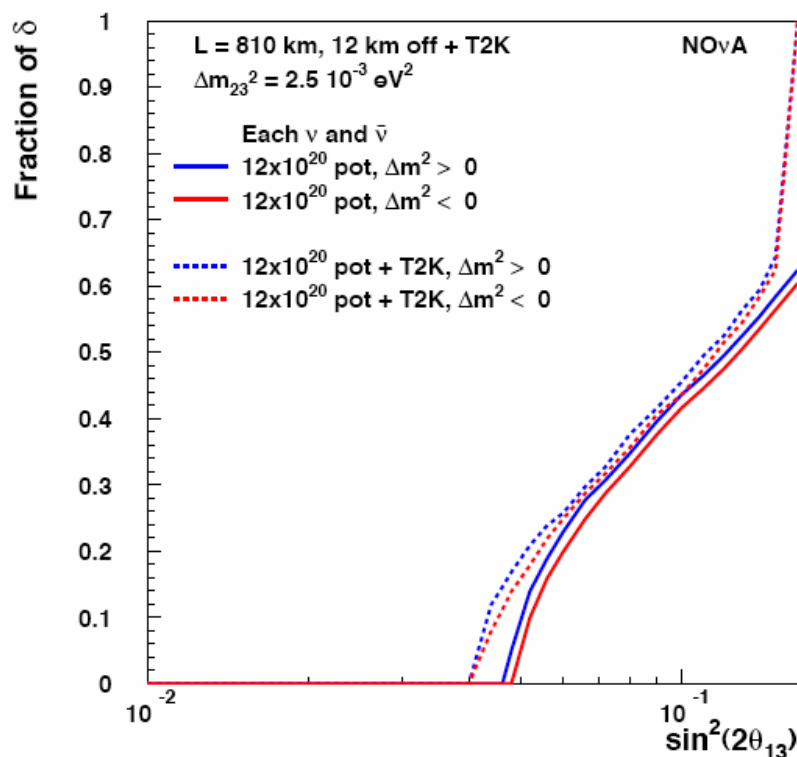
2 σ Resolution of the Mass Hierarchy



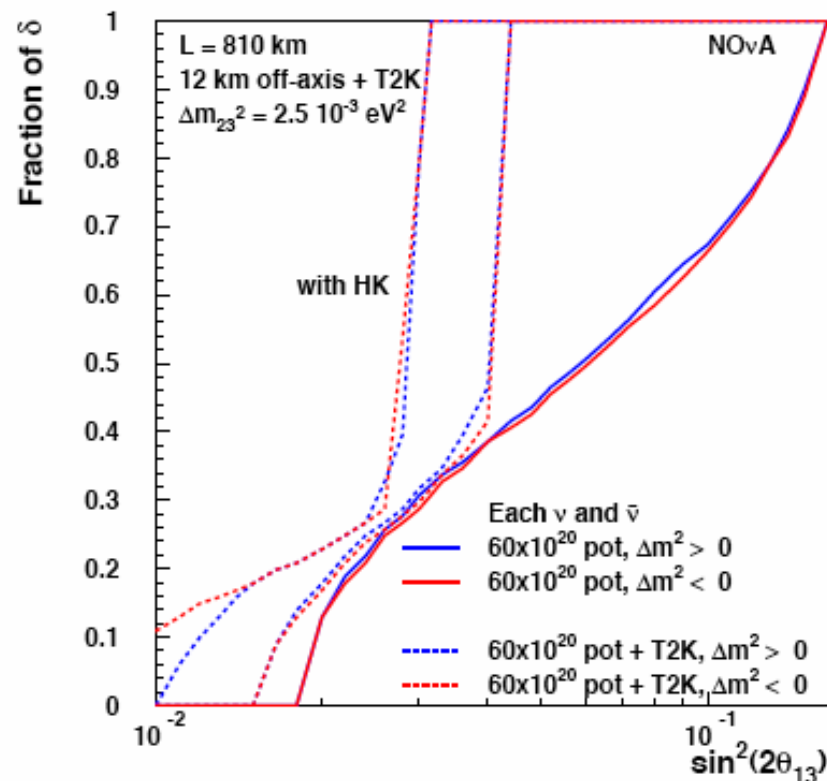
Proton Drivers

Combination with T2K

2 σ Resolution of the Mass Hierarchy

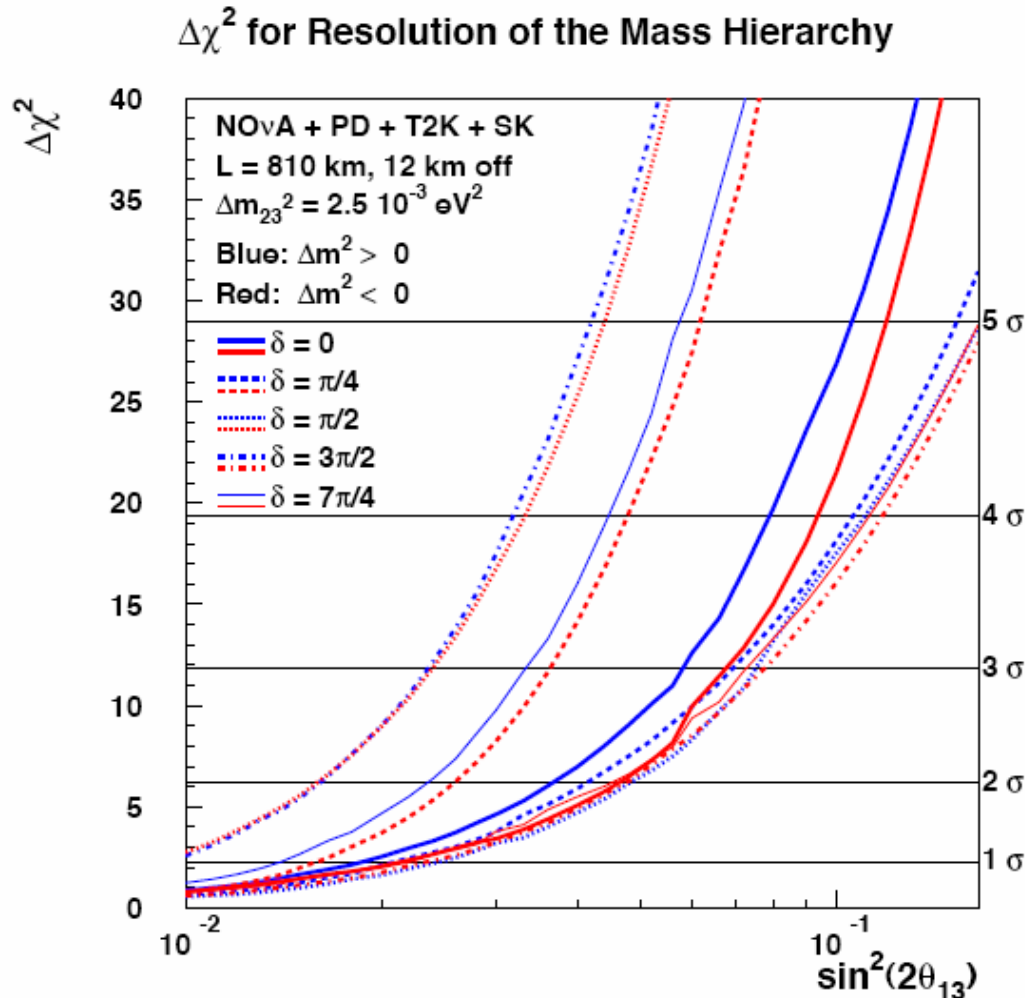


2 σ Resolution of the Mass Hierarchy

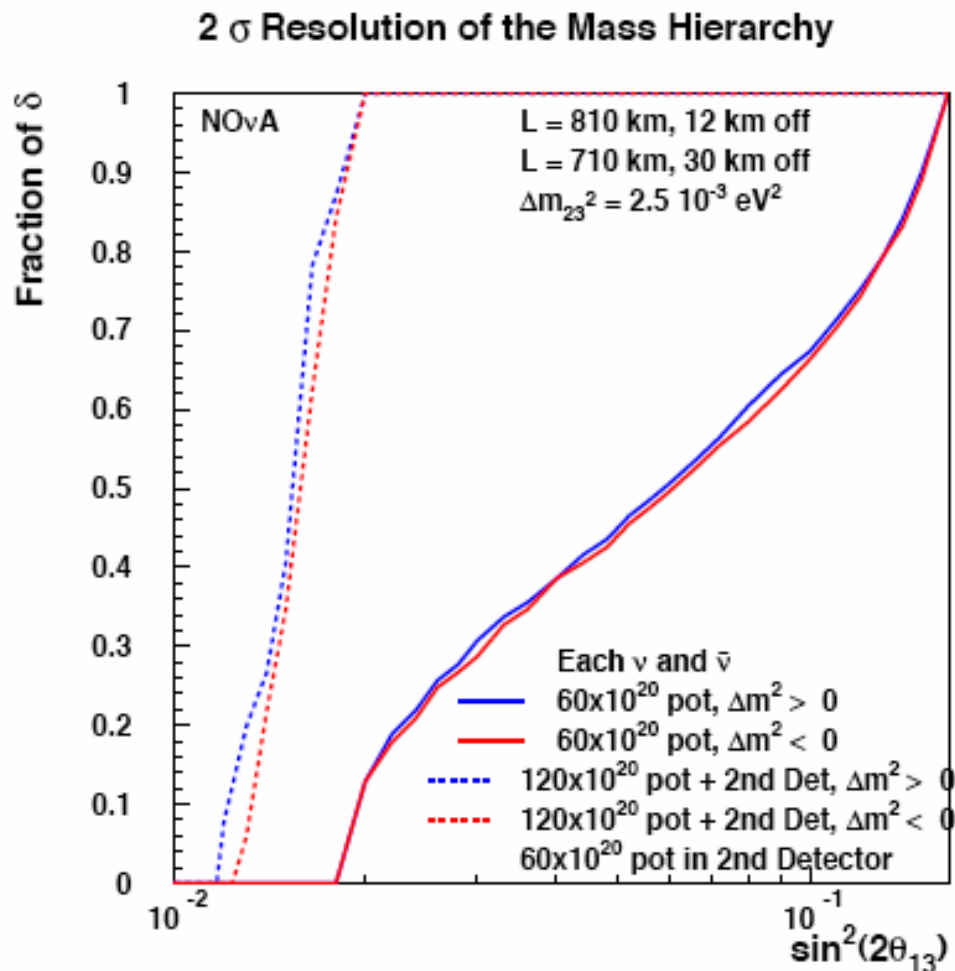


Proton Drivers

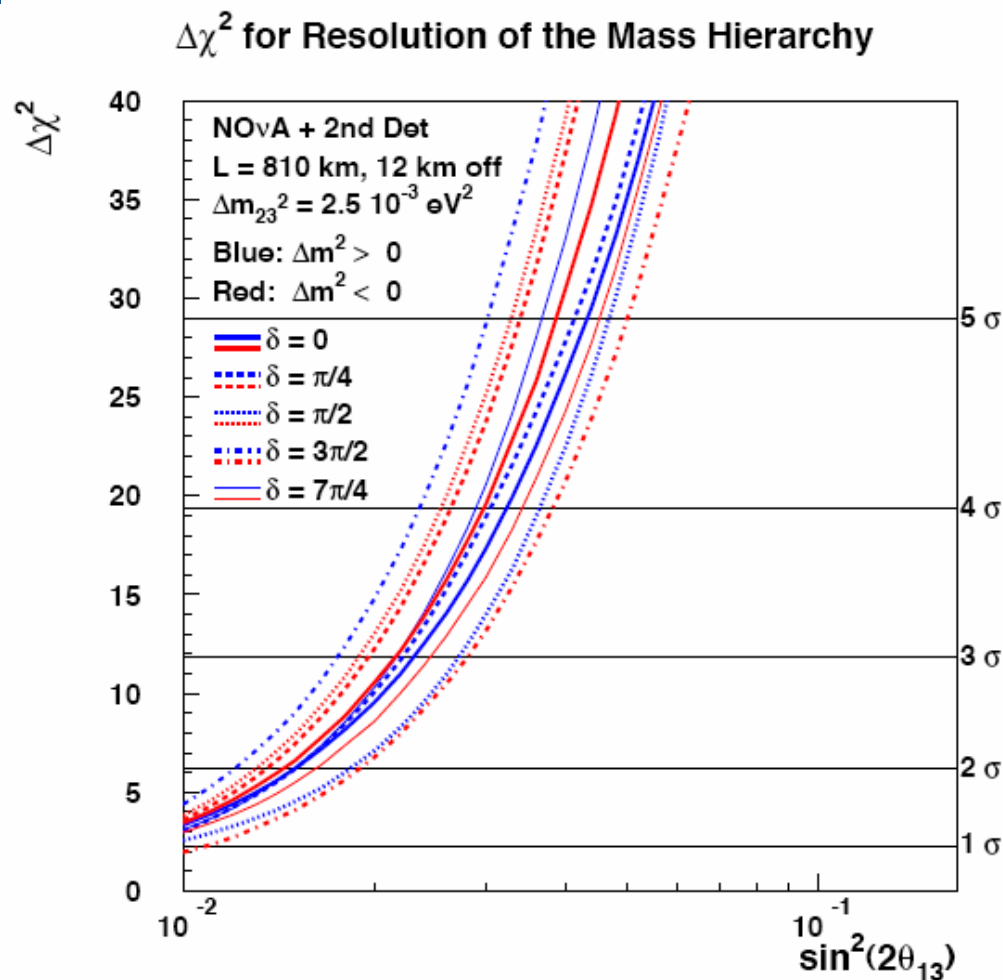
Combination with T2K, with Proton Drivers and SK



Combination with a 2nd OA Detector at the 2nd Maximum

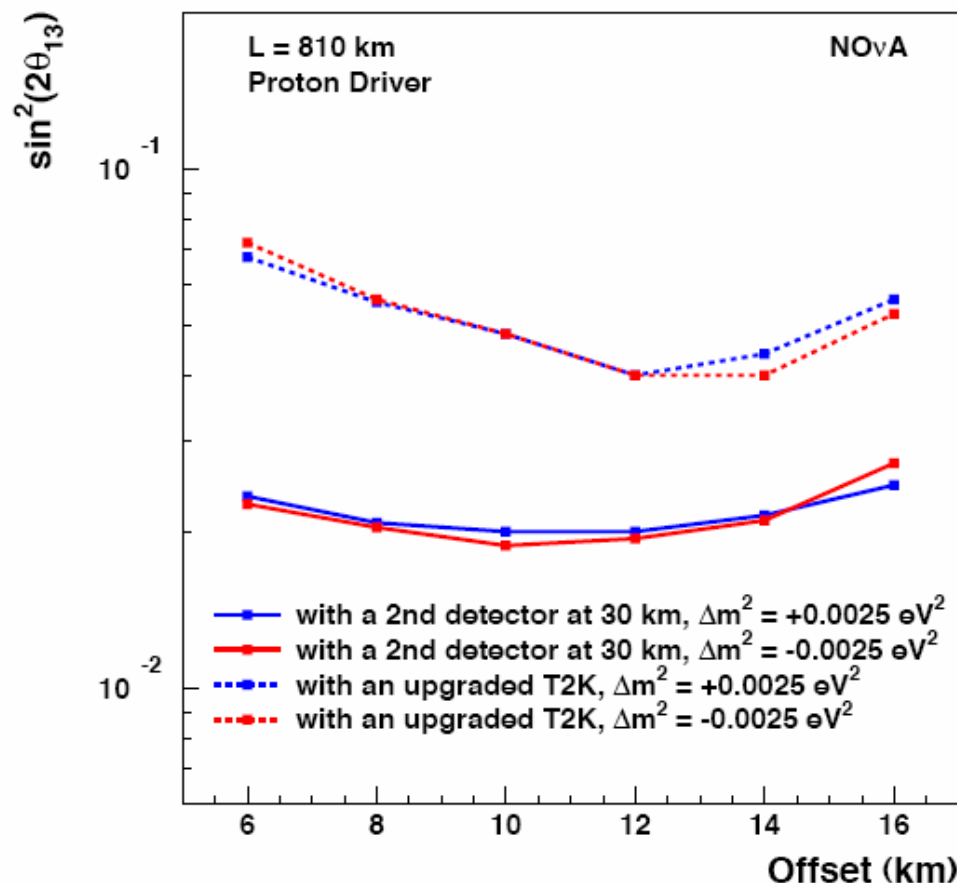


Combination with a 2nd OA Detector at the 2nd Maximum



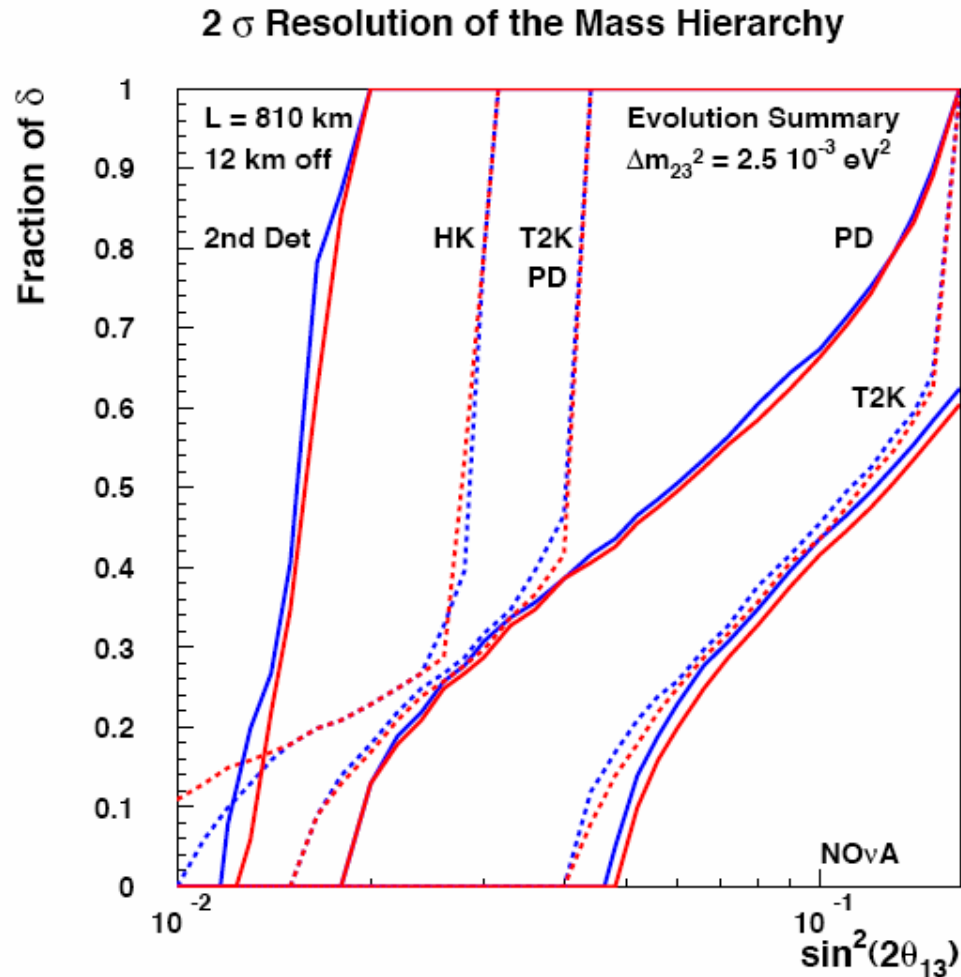
Mass Hierarchy Resolution vs. Off-Axis Distance

2σ Mass Hierarchy Resolution for all δ



Again, 12 km provides a good optimization.

Mass Hierarchy Resolution Summary



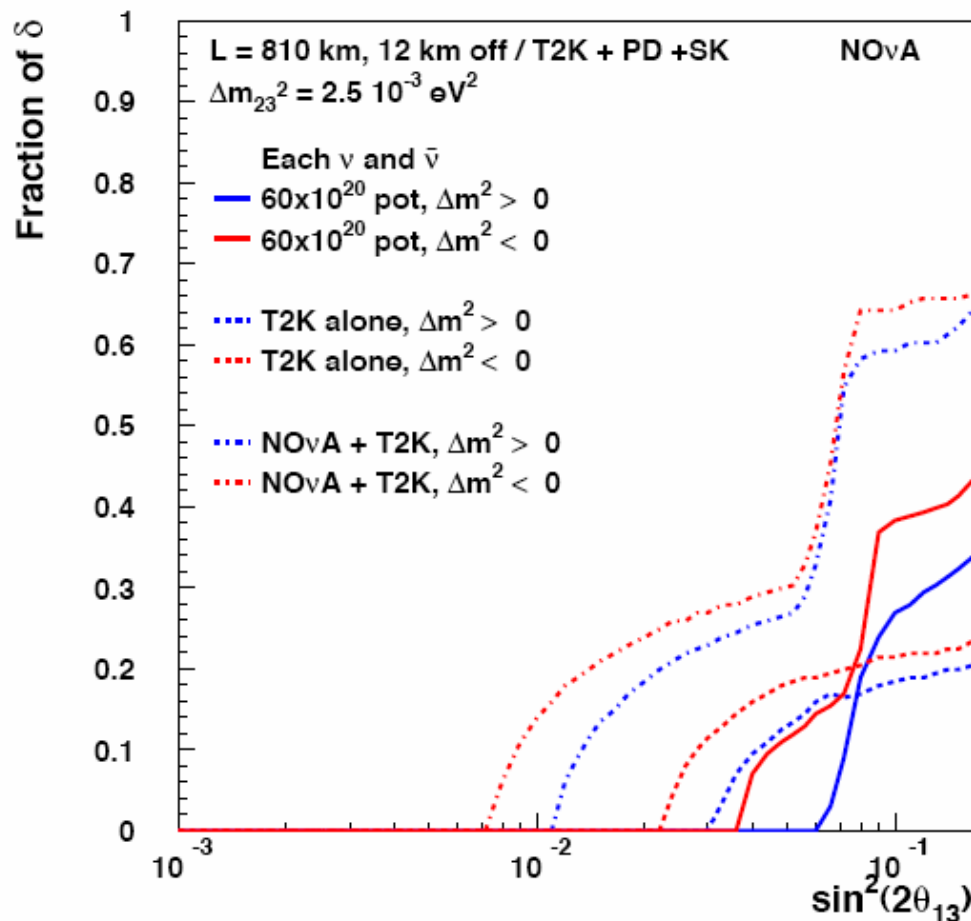


Notes on CP Violation

- Relationship to the mass hierarchy will be different for different experiments.
 - Mass hierarchy unimportant for very short baseline experiments, but crucial for long baseline experiments
- CP violation is first order in θ_{13} , non-CP violating terms are mostly second order.
 - Regions where CP violation is flat in θ_{13} and regions with dips and peaks.
- I will use the criterion of fraction of δ for which there is a 3- σ demonstration of CP violation, i.e., $\delta \neq 0$ or π .

3 σ Demonstration of CP Violation

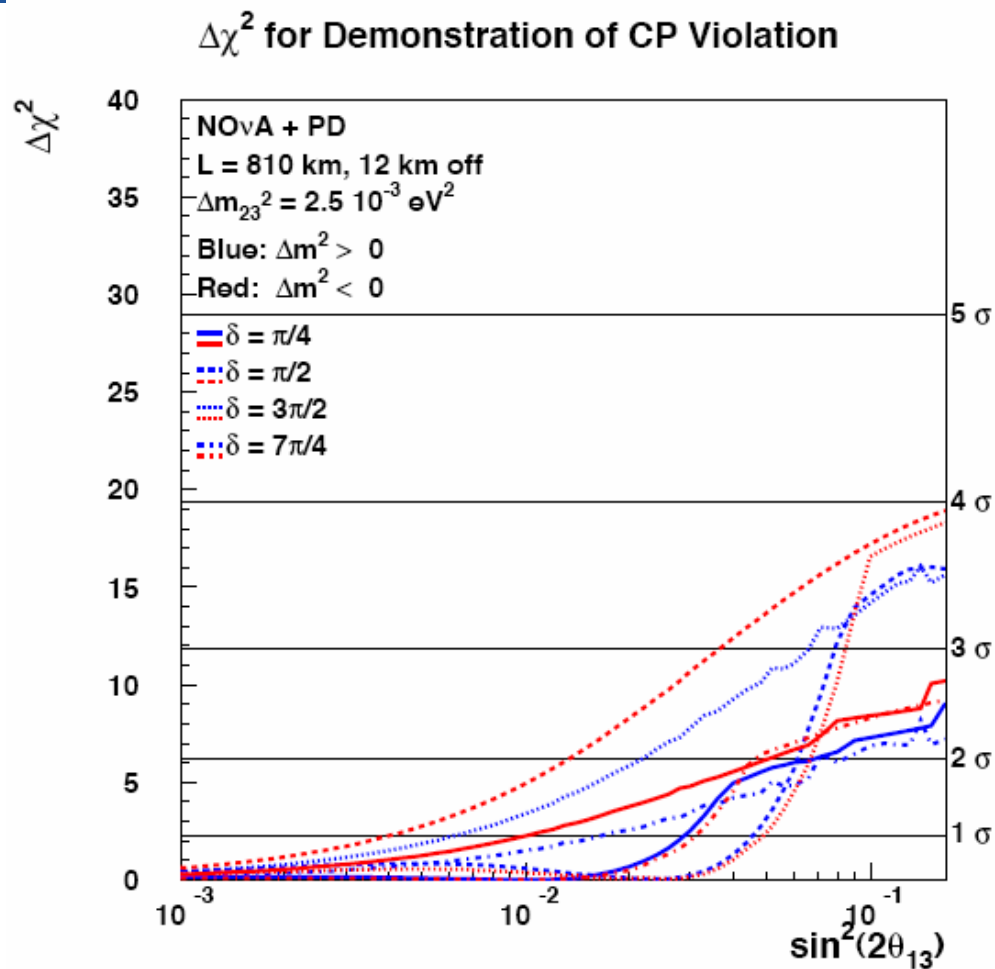
3 σ Determination of CP Violation



**With proton
drivers**

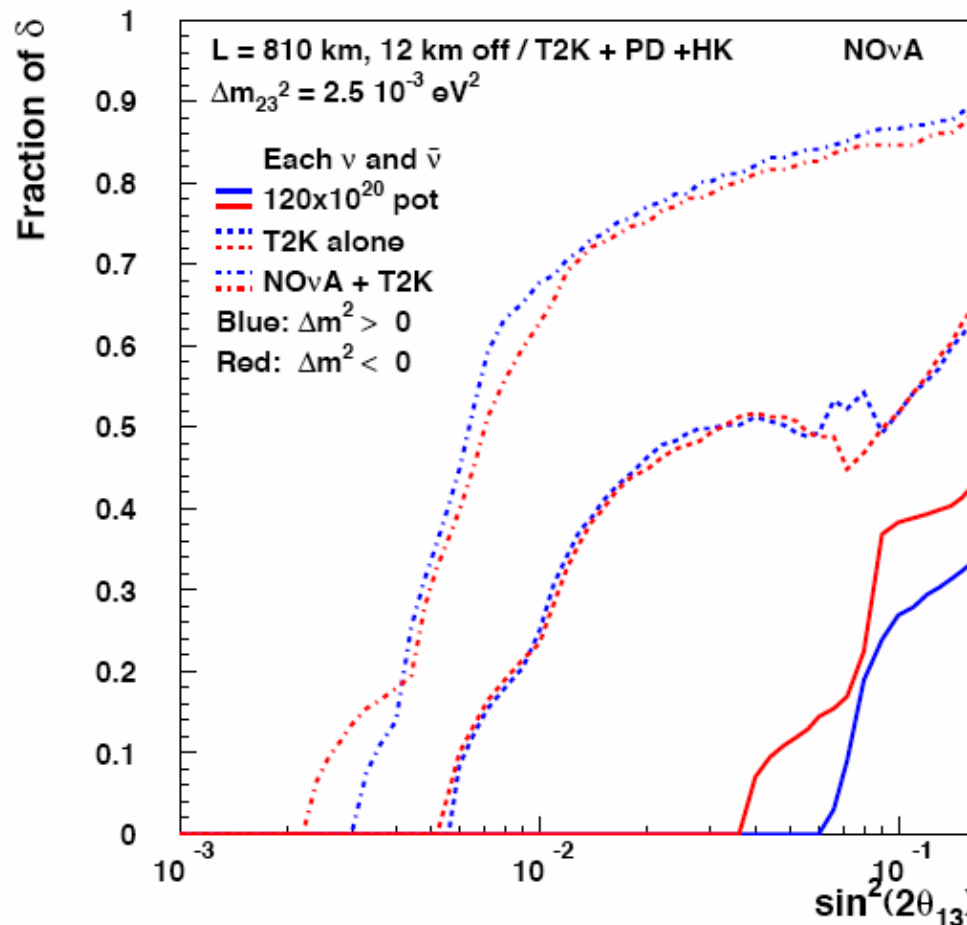
**(No 3 σ CP effect
in either T2K or
NOvA without
them.)**

3 σ Demonstration of CP Violation



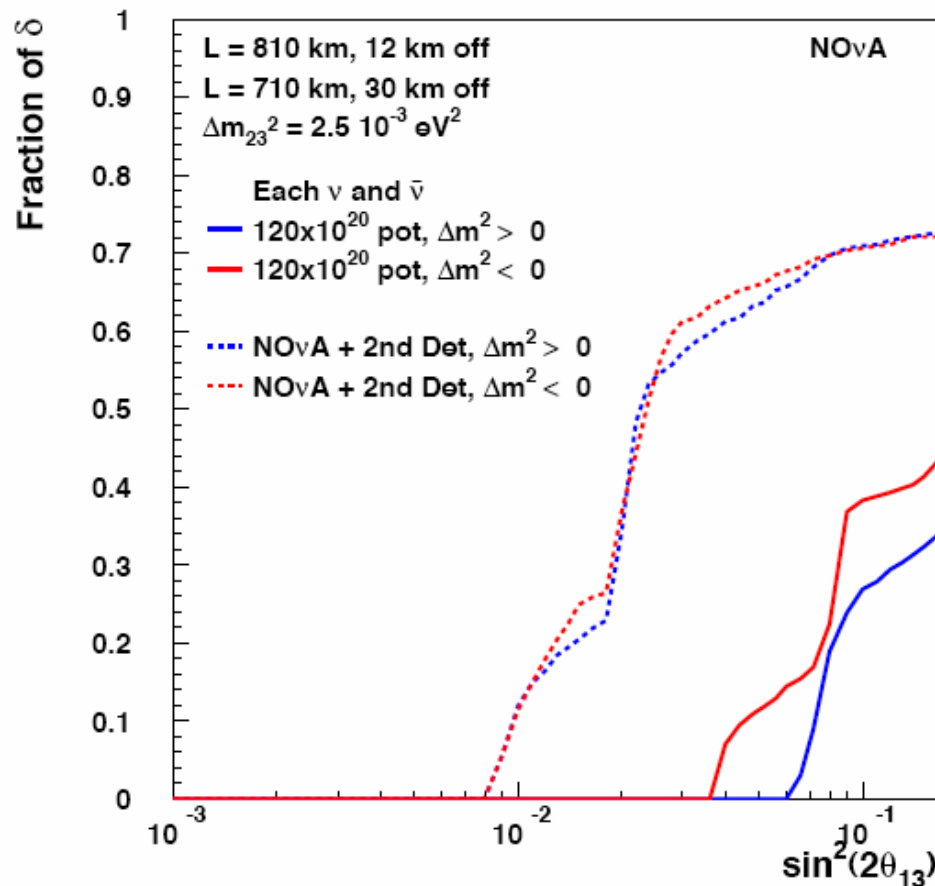
3 σ Demonstration of CP Violation

3 σ Determination of CP Violation



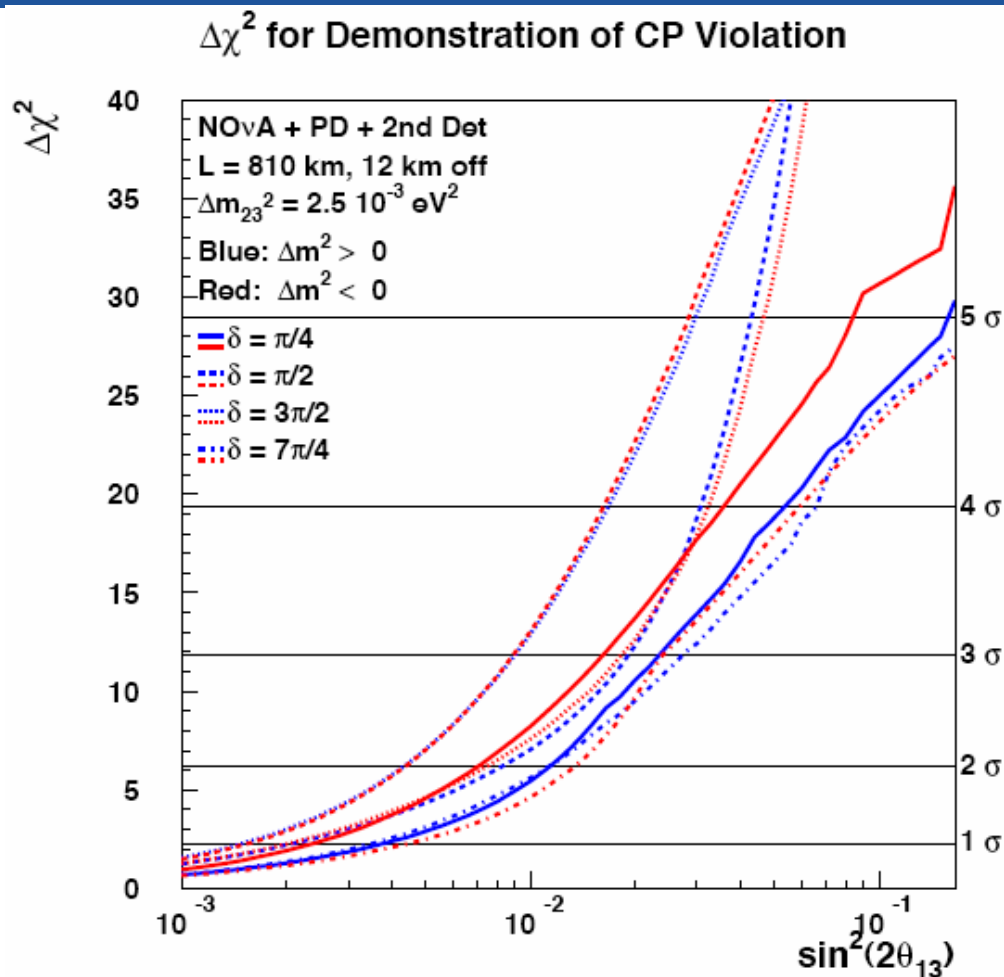
3 σ Demonstration of CP Violation

3 σ Determination of CP Violation



**2nd Off-axis
detector at the
2nd maximum**

Demonstration of CP Violation



**2nd Off-axis
detector at the
2nd maximum**

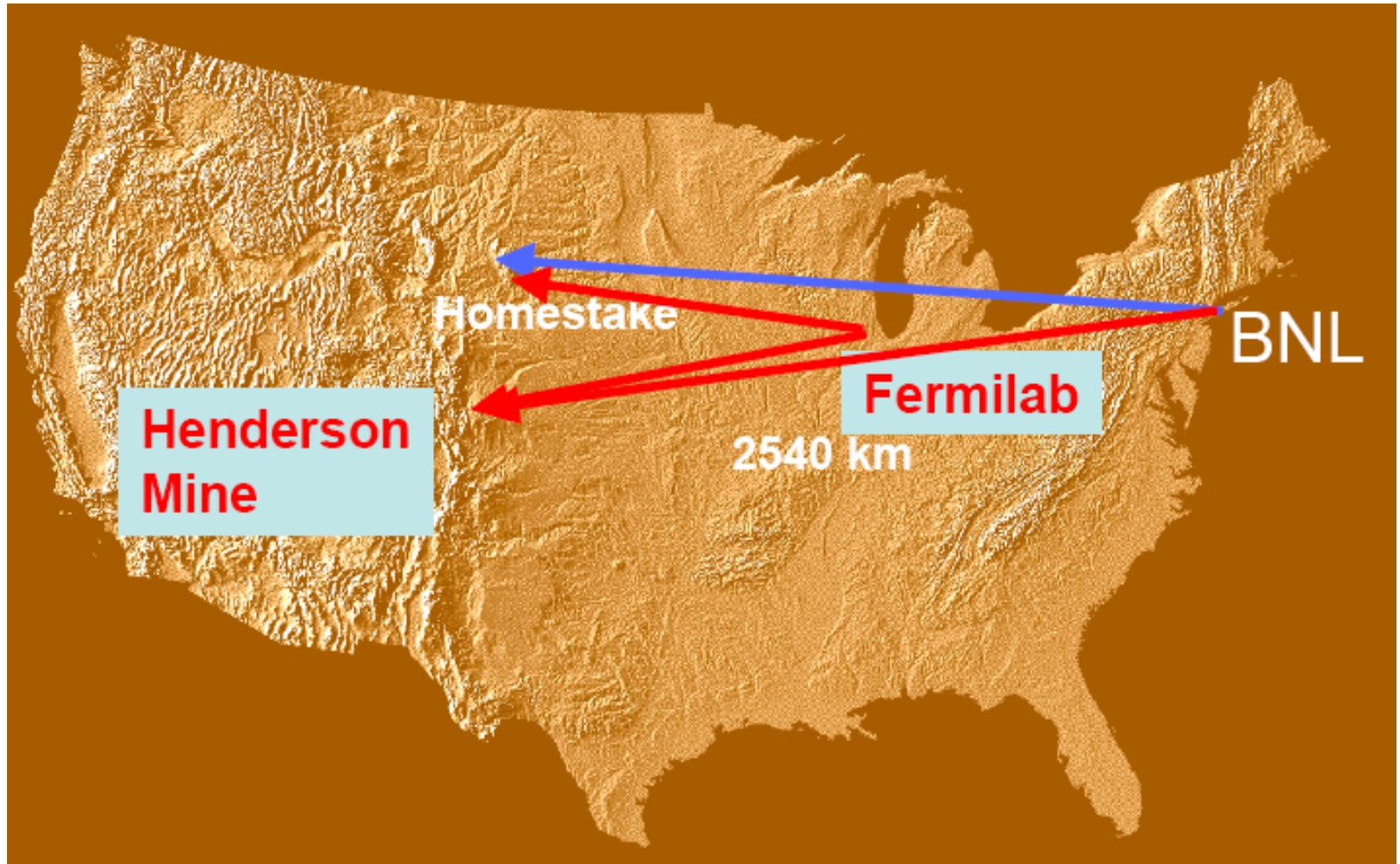
Conclusions

- **NO_vA provides a flexible approach to studying all of the parameters of neutrino oscillations**
 - A long baseline approach is crucial in the context of the world program.
 - NO_vA is the first stage of a flexible program where each stage can be planned according to what has been learned in previous stages.
 - The range of the NO_vA program is comparable to that of other conventional approaches.
 - NO_vA can be started now (same scale as NuMI/MINOS).
 - The approval road is long. We need PAC approval now to keep NO_vA and the Fermilab neutrino program timely.



Backup Slides

Other US Initiatives





Brookhaven White Paper

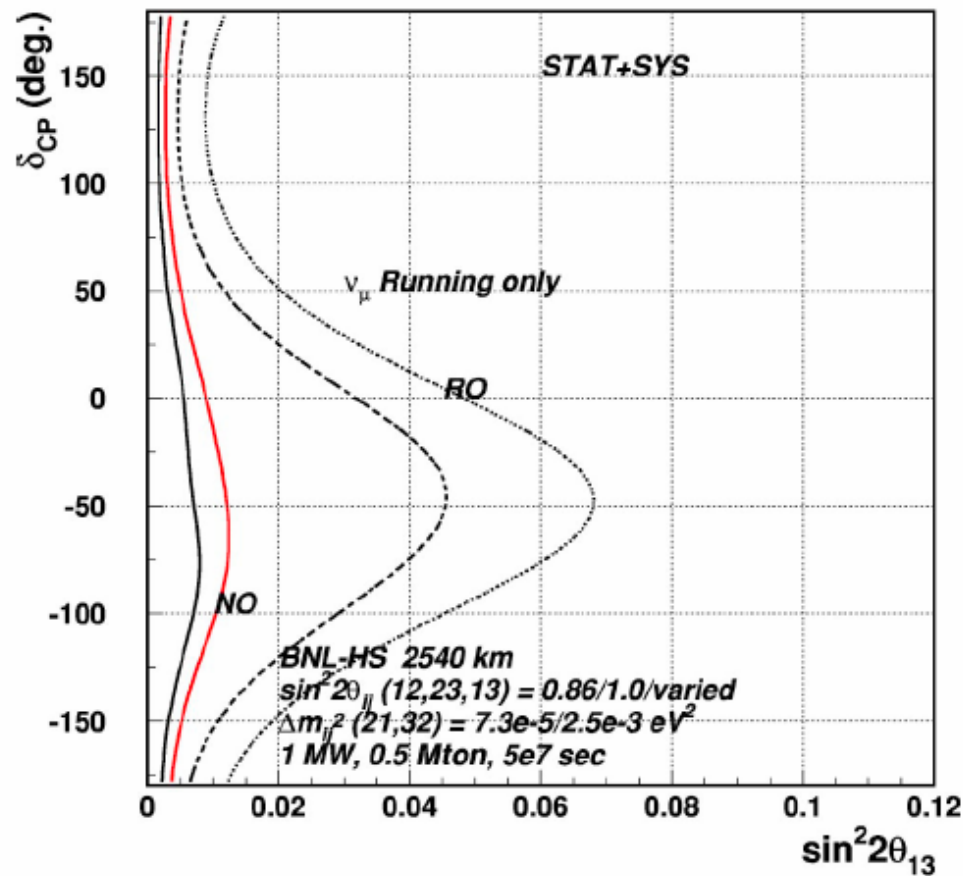
- **Brookhaven has proposed an intense proton source to an on-axis massive detector (500 kT) over a very long baseline (>2000 km).**
 - Idea is to measure all three parameters simultaneously by measuring 3 oscillation maxima.
 - Water Cerenkov does not provide good electron/ π^0 separation above 1 GeV – a factor of 5 better rejection than SuperK is needed. (Liquid argon or TASD?)
 - Range appears to be comparable to the NOvA program, although not explicitly calculated in the same way.
 - Very expensive; could not be done anytime soon, if ever.



NOVA

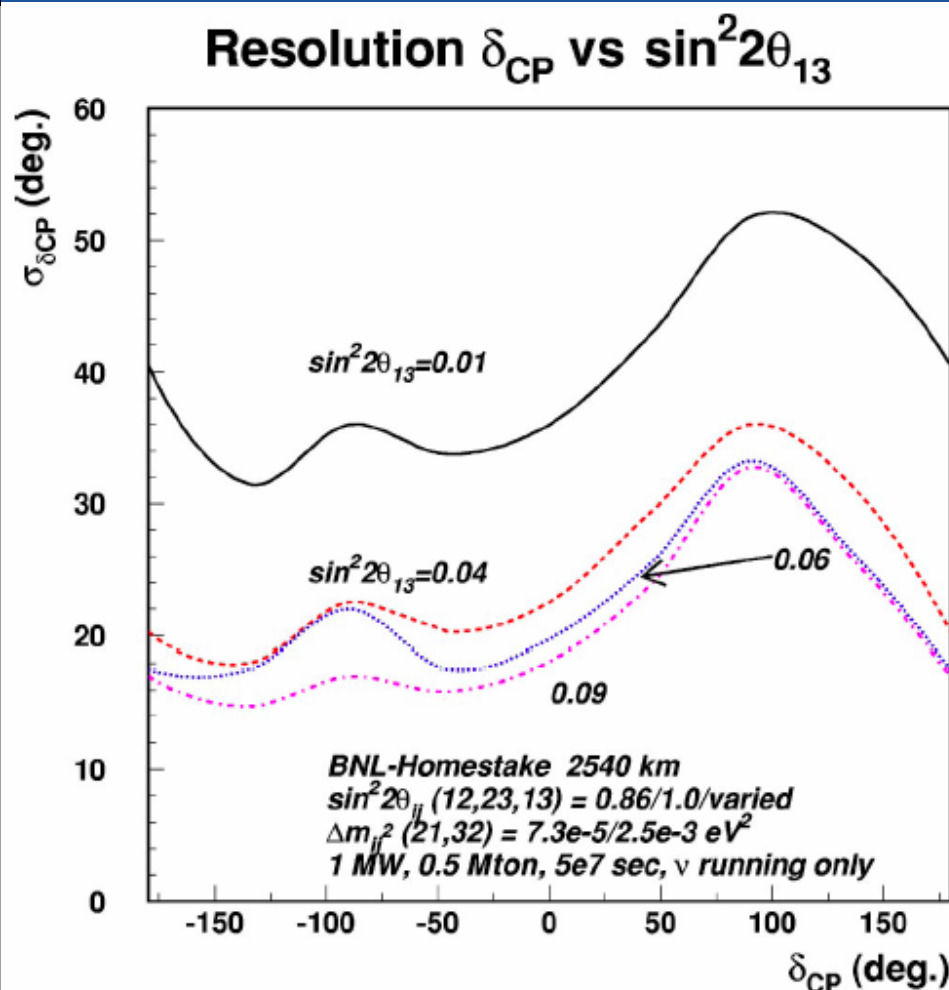
Brookhaven Sensitivity to $\nu_\mu \rightarrow \nu_e$ Signal

90, 99.7 % CL signal, δ_{CP} vs $\sin^2 2\theta_{13}$





Brookhaven Sensitivity to CP Violation



Correspondence
to my 3σ fraction
of δ plot:

← 0

← 0.25

← 0.5

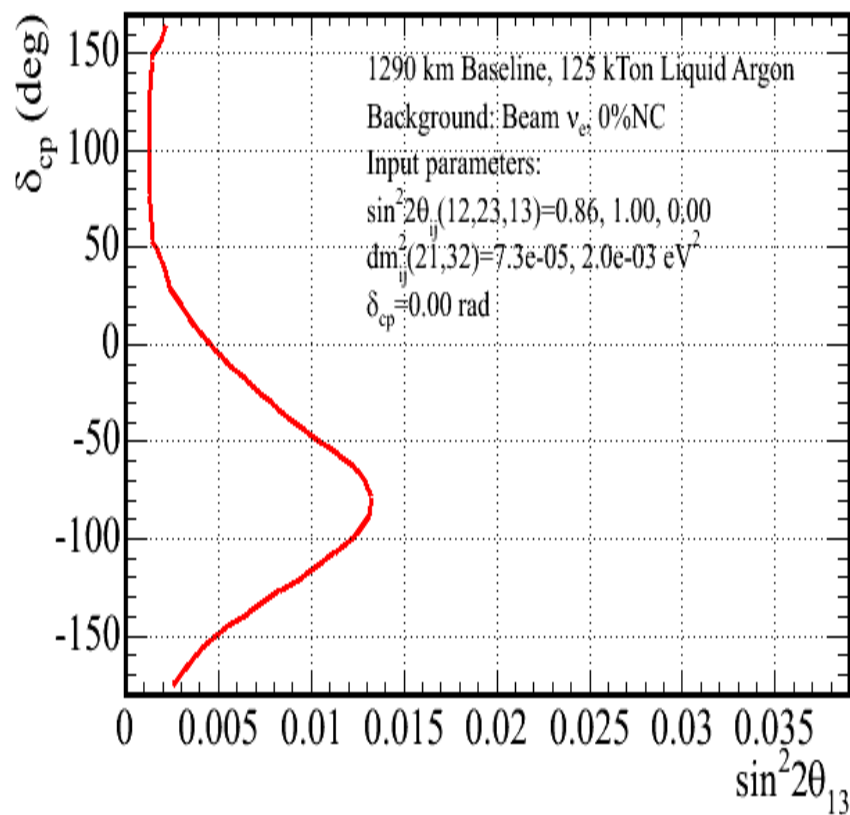


Doug Michael's FeHo Proposal

- Use 4 MW of power from Fermilab, 2 MW from the Proton Driver as an 8 GeV on-axis beam and 2 MW from the Main Injector as a tunable off-axis beam.
- 16 times the flux of Brookhaven proposal (4 from beam x 4 from distance, 1290 km)
- 100-125 kT liquid argon or TASD (4-5 x NOvA)
- Sensitivities not well calculated yet.
- Same comment as Brookhaven on cost and schedule.

FeHo Sensitivity to $\nu_\mu \rightarrow \nu_e$ Signal

90% CL for Excluding Oscillation Parameters



**Note: only 90% CL
and only for the
normal mass ordering**

Only QE events
No NC background
(but all intrinsic
 ν_e included)

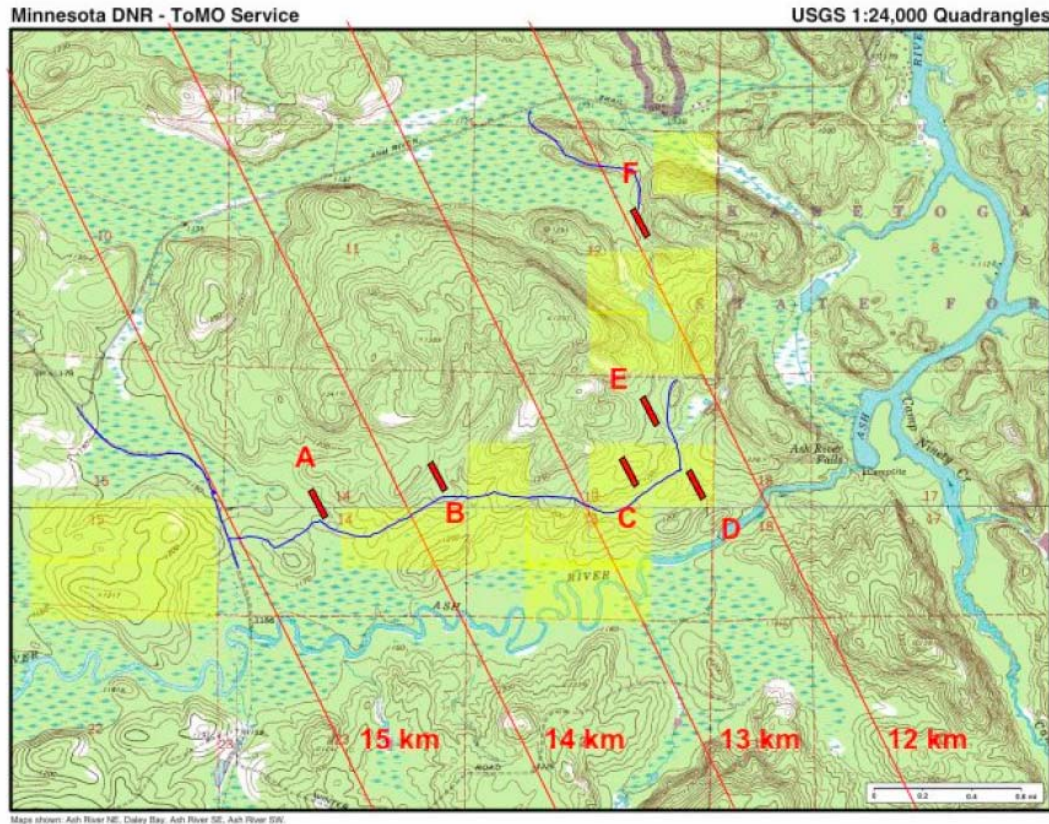


Quick TASD Update

- **Excellent e/μ discrimination**

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Locations at Ash River



**At Ash River, we
Are limited to
Distances > 11 km
Because “a river
Runs through it.”**